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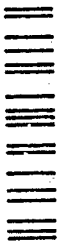


**PROGRAM MANAGER
RMA CONTAMINATION CLEANUP**

U.S. ARMY
MATERIEL COMMAND

— COMMITTED TO PROTECTION OF THE ENVIRONMENT —

AD-A277 509



TECHNICAL SUPPORT FOR
ROCKY MOUNTAIN ARSENAL

DRAFT FINAL
WATER REMEDIAL INVESTIGATION REPORT

(Version 2.2)
Volume I

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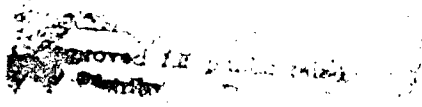
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ROCKY MOUNTAIN ARSENAL

DRAFT FINAL
WATER REMEDIAL INVESTIGATION REPORT

(Version 2.2)
Volume I

March 1989

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Prepared By

EBASCO SERVICES INCORPORATED
R. L. Stollar & Associates, Inc.
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Prepared For

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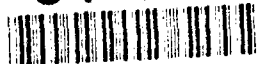
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ACRONYMS AND ABBREVIATIONS

ac-ft	acre-feet
ac-ft/mo	acre-feet per month
ac-ft/yr	acre-feet per year
ACL	alternative concentration limit
Al	A lithologic zone - lower
Am	A lithologic zone - middle
ARAR	Applicable or Relevant and Appropriate Requirement
Army	Department of the Army
As	A lithologic zone - channel
ASTM	American Society for Testing and Materials
ASY	apparent specific yield
atm-m ³ /mole	atmosphere-cubic meter per mole
Au	A lithologic zone - upper
AWQC	ambient water quality criteria
1,2DCLE	1,2 dichloroethane
BTZ	benzothiazole
CC	Contamination Control
CCC	Colorado Climate Center
CCl ₄	Carbon Tetrachloride
CDH	Colorado Department of Health
CDM	Camp Dresser & McKee, Inc.
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CF&I	Colorado Fuel and Iron
cfs	cubic feet per second
CH ₂ Cl ₂	Methylene Chloride
cm/sec	centimeters per second
CMP	Comprehensive Monitoring Program
COE	U.S. Army Corps of Engineers
CPMS	chlorophenylmethyl sulfide
CPMSO	chlorophenylmethyl sulfoxide
CPMSO ₂	chlorophenylmethyl sulfone
CRL	certified reporting limits

ACRONYMS AND ABBREVIATIONS (Continued)

CSU	Colorado State University
CSU-GWFlow	Colorado State University Groundwater Flow Model
CWP	Composite Well Program
CWQ	Clean Water Act
DBCP	Dibromochloropropane
11DCE	1,1-dichloroethylene
11DCLE	1,1-dichloroethane
12DCE	trans-1,2-dichloroethylene
DCPD	Dicyclopentadiene
DIMP	Diisopropylmethyl phosphonate
1,4-DITH	1,4-dithiane
DMDS	dimethyldisulfide
DMMP	dimethylmethyl phosphonate
DOJ	Department of Justice
EA	Endangerment Assessment
EDL	elevated detection limit
EPA	U.S. Environmental Protection Agency
ESE	Environmental Science and Engineering, Inc.
FCP	First Creek Paleochannel
Fm	Formation
FRICO	Farmer's Reservoir and Irrigation Company
FS	Feasibility Study
ft	feet
ft/day	feet per day
ft/ft	feet per foot
ft/sec	feet per second
ft/yr	feet per year
ft ³	cubic feet
FY87	Fiscal Year 1987
gal ft ²	gallons per square foot
GF	nerve gas comprised of Sarin
GC	gas chromatograph
G/ml	gram per milliliter
GC/MS	gas chromatography/mass spectrometry
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ACRONYMS AND ABBREVIATIONS (Continued)

gpd/ft	gallons per day per foot gpd/ft ² gallons per day per square foot
gpm	gallons per minute
H	Henry's Law Constant
HCCPD or CL ₆ CP	hexachlorocyclopentadiene
HGU	Hydrogeologic unit
HLA	Harding Lawson Associates
HSL	Hazardous Substance List
ICAP	inductively-coupled argon plasma
ICS	Irondale Containment System
ID	inside diameter
in/hr	inches per hour
in/mo	inches per month
IRA	Interim Response Action
ISP	Initial Screening Program
K	hydraulic conductivity
K _{oc}	organic carbon partition coefficient
K _d	partition coefficient
K _{ow}	octanol/water partition coefficient
LA	Lignite A
LB	Lignite B
lbs/ft ³	pounds per cubic foot
LC	Lignite C
LD	Lignite D
MCL	maximum contaminant level
MCLG	maximum contaminant level goal
mg/l	milligrams per liter
mi	miles
MIBK	methylisobutyl ketone
MIKE	Morrison-Knudsen Engineers, Inc.
mm	millimeter
mph	miles per hour
msl	mean sea level
NBCS	North Boundary Containment System

ACRONYMS AND ABBREVIATIONS (Continued)

NBTP	North Boundary Treatment Plant
NBW	north boundary west
NTC	nontarget compounds
NWBCS	Northwest Boundary Containment System
NWBP	Northwest Boundary Paleochannel
O&M	operation and maintenance
O ₃	ozone
PAS	Parties and the State
OCP	organochlorine pesticide
OD	outside diameter
°F	degrees Farenheit
OXAT	oxathiane
OX/DITH	Combined oxathiane and dithiane
PCE	tetrachloroethylene
PI	plasticity index
PID	photoionization detector
PMO-RMA	U.S. Army Program Manager's Office for Rocky Mountain Arsenal Contamination Cleanup
PMSO	Program Manager Staff Office
p,p'-DDE	p,p'-1,1-dichloro-2,2-bis(4-chlorophenyl)-ethylene
p,p'-DDT	p,p'-dichlorodiphenyltrichloroethane
PPLV	Preliminary Pollutant Limit Value
ppm	parts per million
psi	pounds per square inch
PVC	polyvinyl cnloride
QA1	Paleochannels in terrace gravels
QA2	Paleochannels in eolian deposits (w/gravels)
QA3	Silty terrace gravels and coarse sand
QA4	Paleochannels in eolian deposits (w/o gravels)
QAE	Eolian deposits
QA/QC	Quality Assurance/Quality Control
QC	Quality control
QT	Quaternary terrace gravels
RCI	Resource Consultants, Inc.

ACRONYMS AND ABBREVIATIONS (Continued)

RCRA	Resource Conservation and Recovery Act
R _f	Retardation factor
RI	Remedial Investigation
RI/FS	Remedial Investigation/Feasibility Study
RIC	RMA Information Center
RMA	Rocky Mountain Arsenal
RMACCPMT	Rocky Mountain Arsenal Control Management Team
ROD	Record of Decision
SACWSD	South Adams County Water and Sanitation District
SAR	Study Area Report
SARA	Superfund Amendments and Reauthorization Act
SCC	Shell Chemical Company
SCS	Soil Conservation Service
SDWA	Safe Drinking Water Act
Shell	Shell Chemical Oil Company
SO ₂	Sulfur Dioxide
sq mi	square mile(s)
STP	Sewage Treatment Plant
SW/GW	surface water/groundwater
T	transmissivity
1,1,1-TCE	1,1,1-trichloroethane
1,1,2-TCE	1,1,2-trichloroethane
TCLEE	tetrachloroethylene
TIC	tentatively identified compounds
TKd	Denver Formation
TRCLE	trichloroethylene
TSP	total suspended particulates
1u	number one upper zone in the Denver Fm
ug/g	micrograms per gram
ug/l	micrograms per liter
UFS	Unconfined Flow System
UNK	unknown
USATHAMA	U.S. Army Toxic and Hazardous Materials Agency
USCS	Unified Soil Classification System
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ACRONYMS AND ABBREVIATIONS (Continued)

UTM	Universal Transverse Mercator
VC	volcaniclastic interval
VCE	clay-rich zone stratigraphically equivalent to VC
VOA	volatile organic aromatics
VOC	volatile organic compounds
VOH	volatile organohalogens
WES	U.S. Army Corps of Engineers Waterways Experiment Station
WRI	Water Remedial Investigation
WY87	Water Year 1987

EXECUTIVE SUMMARY

The purpose of the Water Remedial Investigation Report is to present results of the U.S. Department of the Army Remedial Investigation for the Rocky Mountain Arsenal (RMA) on-post water media. The Water Remedial Investigation assesses contaminant occurrence and distribution within groundwater and surface water. To accomplish the assessment, the RMA environmental setting was evaluated in terms of geology, hydrology, nature and extent of water-borne contamination, and contaminant migration.

Soil, groundwater, and surface water became contaminated locally as a result of past military and industrial activities. With time, contaminants entered the groundwater system and were transported off-post, creating a threat to downgradient water wells. On-post contamination resulted from unintentional spills, waste disposal practices, and sewer-line leakage. The number and concentration of contaminants present in RMA groundwater have changed through time.

Environmental Setting

RMA is part of the High Plains physiographic province, and is characterized by gently rolling hills with a total change in altitude of 220 ft and average annual precipitation of approximately 15 inches. Surface water flows within several small drainage basins that are tributaries of the South Platte River. The major drainages within RMA boundaries are First Creek and Irondale Gulch. Manmade structures including diversion ditches, lakes, and water retention basins have modified the natural drainage patterns.

The surficial geologic units at RMA consist of unconsolidated alluvial and eolian deposits, and the underlying geologic unit is the Denver Formation. Alluvial and eolian deposits locally attain a thickness of 130 ft but typically are less than 50 ft. Several prominent paleochannels have been identified in the erosional surface of the Denver Formation. Bedding planes in the Denver Formation dip approximately 1° to the southeast. The Denver Formation consists of lenticular sandstone and siltstone bodies interlayered with relatively thick sequences of low permeability shale and claystone. Lignitic beds are laterally more continuous than sandstone layers and commonly are fractured. Total thickness of the Denver Formation at RMA varies from 200 to 500 ft.

Groundwater at RMA occurs under both confined and unconfined conditions. The Unconfined Flow System includes saturated alluvium, eolian deposits, and occasionally, subcropping parts of the Denver Formation. In areas where alluvial and eolian deposits are unsaturated, the Unconfined Flow System consists solely of sandstone, and of fractured or weathered rock within shallow parts of the Denver Formation. Saturated thickness varies from less than 10 ft to approximately 70 ft. Hydraulic conductivity estimates from aquifer tests range from 0.3 ft/d in areas where the Denver Formation is unconfined to greater than 900 ft/d in alluvial terrace gravel.

Groundwater in the Unconfined Flow System generally flows toward the north and northwest. Spatial variations in hydraulic gradients can be attributed to variations in saturated thickness, hydraulic conductivity, locations of recharge and discharge, and configuration of the bedrock surface. Hydraulic gradients in areas of saturated alluvium typically are 0.002 to 0.009 ft/ft. Gradients in areas of unconfined Denver Formation typically are larger. Water level fluctuations generally are small; however, seasonal fluctuations as large as 7 ft have been measured beneath South Plants. Historical water level fluctuations have been large in the vicinity of Basin C. During the late 1950s and from 1969 through 1975, water levels beneath Basin C rose 20-30 ft in response to artificial recharge. Present day recharge to the Unconfined Flow System occurs as infiltration of precipitation and irrigation, seepage from lakes and streams, seepage from reservoirs, canals and buried pipelines, and flow from the underlying Denver aquifer. Discharge occurs primarily as seepage to lakes and the South Platte River.

Mass balance calculations have been used to estimate rates of hydraulic interchange between lakes and the Unconfined Flow System. Results indicate that Lower Derby Lake, Havana Pond, and Basins B through F are areas of groundwater recharge, whereas Lake Ladora, Lake Mary, and Basin A receive groundwater in upstream areas and lose it in downstream areas. Recharge-discharge conditions at Upper Derby Lake depend on lake level. Streamflow loss and gain studies indicate that all streams and canals at RMA lose water to the Unconfined Flow System over the course of a water year. However, actual recharge or discharge rates vary substantially in response to changes in stream discharge and aquifer head. During periods of negligible streamflow, First Creek north of the RMA boundary gains groundwater at a small rate.

A numerical model of groundwater flow in the Unconfined Flow System has been developed to evaluate hydrologic concepts and refine hydraulic conductivity estimates. Model calibration consisted of adjusting hydraulic parameters until simulated hydraulic head adequately reproduced measured water levels. With few exceptions, model calibration was achieved without modifications to initial estimates of hydraulic parameters. Model results confirmed that paleochannels and terrace deposits generally convey larger flows than interfluvial zones. Hydraulic conductivity estimates in the Basin A Neck and areas immediately northwest obtained during model calibration were smaller than initial estimates. Sensitivity analyses indicated that the areas of greatest model uncertainty within the boundaries of RMA are near South Plants and Basins A through F.

The Denver aquifer in the vicinity of RMA consists of parts of the Denver Formation where water is under confined conditions. Generally, confined conditions are observed within permeable sandstone or lignitic beds that are separated from the Unconfined Flow System by relatively impermeable shale or claystone. The hydraulic conductivity of the shale and claystone matrix is small, probably 10^{-2} to 10^{-4} ft/d. The hydraulic conductivity for sandstone in the Denver aquifer has been estimated by pumping test analyses to range from 1.1 to 7.7 ft/d. The hydraulic conductivity of fractured lignitic beds may be an order of magnitude greater than the hydraulic conductivity of sandstone.

Hydrogeologic cross sections and potentiometric surface maps indicate that there is potential for groundwater in the Denver aquifer to move downward and laterally toward the northwest. The smaller hydraulic conductivity of shale relative to sandstone, as well as the stratification of the Denver aquifer, probably restricts the rate of vertical flow while enhancing lateral flow. Water in transmissive strata of the Denver aquifer returns to the Unconfined Flow System by lateral flow in areas where the elevation of the bedrock varies appreciably in a short distance and the transmissive strata subcrop. Initial efforts to estimate rates of hydraulic interchange have been based on an assumption that flow from the Denver aquifer to the Unconfined Flow System occurs in all areas of subcropping sandstone. The estimated rate of discharge was 600 acre-ft/yr.

A cross-sectional numerical model was developed to gain a better understanding of flow mechanisms within the Denver aquifer. The model was constructed approximately along a flow path from Upper Derby Lake to the Basin A Neck. A variety of layered heterogeneous flow systems were hypothesized and sensitivity analyses for each system

were completed. Results indicate that shale and claystone layers have low vertical hydraulic conductivity and provide a high degree of confinement within the Denver aquifer. Hydraulic conductivity of sandstone was estimated during model development to range from 0.3 to 3.0 ft/day and hydraulic conductivity of lignitic beds was estimated to be an order of magnitude greater.

Nature and Extent of Contamination

The nature and extent of contamination is based primarily on analytical results from Third Quarter FY87 sampling. These results have been compared to previous water-quality data when appropriate. In this report, individual analytes have been consolidated into composite groups on the basis of analytical methodology. Individual analytes within a group generally have similar physical and chemical characteristics.

Areas where surface water contamination was detected during the Third Quarter FY87 sampling period include South Plants, Basin A and the Sewage Treatment Plant. Organochlorine pesticides and organosulfur compounds were the most frequently detected analytes. Fewer contaminants were detected from water entering RMA along the Peoria Interceptor. Comparisons of Third Quarter FY87 data with previously collected data indicate that there is little difference in analyte concentration at a site through time.

Groundwater contaminant pathways have been identified primarily on the basis of plume configuration. Pathways conform to groundwater flow lines that have been inferred from the potentiometric surface map of the Unconfined Flow System. Pathway names are based on proximity to well known fractures and may not indicate the source of a particular contaminant plume. Contaminant pathways include South Plants, Basin A-Basin A Neck, Central, Basin F, Western Tier, and Motor Pool and Railyard. Several secondary pathways and off post pathways also have been named.

The majority of contamination by organic compounds occurs in the Unconfined Flow System. Volatile halogenated organic plumes have been identified along all major pathways with peak concentrations of 39,800 ug/l occurring along the Basin F pathway. Peak concentrations of 56,200 ug/l have been detected near Basin A for volatile aromatic organics. Plumes of volatile aromatic organics occur along South Plants, Basin A-Basin A Neck and Basin F pathways. Plumes of organosulfur compounds occur along the Basin A-Basin A Neck and Basin F pathways. Plumes of diisopropylmethyl phosphonate are more

extensive than other organic compounds and have been identified along all major pathways. Peak concentration is 5,200 ug/l. Plumes of organochlorine pesticides with peak concentrations greater than 1.0 ug/l have been identified in the South Plants, Basin A-Basin A Neck, Central, and Basin F pathways. Organic plumes have also migrated along off-post pathways.

Inorganic contaminants are more areally extensive in the Unconfined Flow System than organic compounds. Arsenic plumes have been delineated in the Basin A-Basin A Neck and Basin F pathways. A 410 mg/l peak concentration of arsenic occurred in the Basin F pathway. Fluoride concentrations greater than 5,000 ug/l were measured in the vicinity of Basin A and Basin F. Chloride concentrations greater than 1,000,000 ug/l were measured along the Basin A-Basin A Neck, Central, and Basin F pathways. The distribution of inorganic contaminants is complicated by the natural occurrence of these substances.

Concentrations of organic compounds in the Denver aquifer generally are less than concentrations in the overlying Unconfined Flow System. Volatile aromatic organics and diisopropylmethyl phosphonate have been identified over a more extensive area than other organic groups. Organosulfur compounds are common in upper stratigraphic zones of the Denver aquifer beneath the Basin A-Basin A Neck pathway and beneath Basin C. Organochlorine pesticides generally occur in isolated areas, rather than plumes. Other organic compounds occur only in isolated areas. In Sections 1, 2, 3, 9, 19, 23, 24, 26, 27, 33, 35, and 36 samples from the deepest wells in the Denver aquifer contained measurable concentrations of one or more organic contaminants. Organic analytes detected in water from deeper stratigraphic zones of the Denver aquifer generally have been located in the area between Basin F and off post Sections 13 and 14 (T2S R67W).

Inorganic analytes above background levels have been detected in water of the Denver aquifer; however, concentrations generally decrease with increasing depth. Concentrations of chloride in the Denver aquifer north and northwest of Basin F are less than 15,000 ug/l. Fluoride concentrations in this area are less than 2,500 ug/l. Chloride concentrations in the Denver aquifer beneath Basin A-Basin A Neck are generally less than 250,000 ug/l. Fluoride concentrations in this area are generally less than 2,000 ug/l.

Contamination Assessment

Changes in contaminant concentrations of groundwater at RMA are due to advective transport, hydrodynamic dispersion, dilution, and several hydrochemical processes. Advection is migration at the average rate of water molecules and is described by the average linear velocity of groundwater flow. Descriptions of migration due to advection along selected flow paths are given later in this section. Hydrodynamic dispersion describes deviations from the average rate of migration. While regional assessments of dispersion have been completed, evaluations along specific flow paths have not been attempted. Changes in concentration due to dilution are important in areas where potentiometric surface maps show converging flow paths. The predominant hydrochemical processes affecting changes in contaminant concentration are sorption, vaporization, and degradation. Distribution coefficients (K_d) for RMA contaminants indicate that organochlorine pesticides are generally strongly sorbed while organosulfur compounds are generally weakly sorbed. Volatile aromatic organics and volatile halogenated organics tend to vaporize readily to the unsaturated zone.

Contaminant migration from the South Plants area occurs along several pathways. Pathways radiate in several directions from a water table mound beneath South Plants. Numerous contaminants have been detected along a pathway from South Plants toward Basin A. Contaminants include organochlorine pesticides, organosulfur compounds, volatile halogenated organics, volatile aromatic organics, and others. Estimates of groundwater travel time from the center of the water table mound beneath South Plants to the center of Basin A range from 4.1 to 34 years. Volatile halogenated organics and volatile aromatics occur as plumes along a pathway from the South Plants through unconfined Denver Formation toward Ladora Lake. Estimates of groundwater travel time from the center of the water table mound to Ladora Lake range from 16 to 160 years.

Contaminant migration from Basin A is principally toward the northwest in a small area of saturated alluvium called the Basin A Neck. Secondary pathways trending generally north from the Basin A-Basin A Neck also may exist in unconfined parts of the Denver Formation. Groundwater contaminants that occur in greatest concentrations along the Basin A-Basin A Neck pathway include dithiane, oxathiane, benzene, chlorobenzene, chloroform, diisopropylmethyl phosphonate, fluoride and chloride. Estimates of groundwater travel time from Basin A to the down-gradient end of Basin D range from 12.3 to 49.4 years. Dithiane and oxathiane are weakly sorbing contaminants and have been

used to compare average linear velocity and groundwater travel time calculated from available hydraulic information with actual contaminant travel time. The comparison was most favorable when assuming an effective porosity of 0.31.

Contaminants moving through the Basin A Neck continue to migrate along one of several central pathways toward the Northwest Boundary Containment System. Other central pathways originate near the Sand Creek Lateral or Basin F and also trend toward the Northwest Boundary Containment System. Hydraulic conductivity is less and hydraulic gradient is greater along the upgradient part of these pathways than along the downgradient part. Estimates of groundwater travel time from the down-gradient end of Basin D to the Northwest Boundary Containment System range from 6.7 to 27 years. Calculated groundwater travel time along these pathways compares well with travel time of contaminants that are weakly adsorbed. The comparison with diisopropylmethyl phosphonate was most favorable when assuming an effective porosity range from 0.25 to 0.35. The comparison with chloroform was most favorable when assuming an effective porosity of 0.40.

Contaminant migration from source areas beneath Basin C and Basin F occurs in alluvial material and weathered bedrock. The Basin F pathway trends north to the North Boundary Containment System. Most target contaminants occur near Basin F or along the Basin F pathway. Saturated thickness along the pathway typically is less than 10 ft and hydraulic gradients are very low. Saturated thickness and hydraulic gradients in recent years are substantially less than gradients from 1957 to 1971 when Basin C was used as an artificial recharge basin. Assuming effective porosity values between 0.1 and 0.4, present day groundwater travel time from Basin F to the North Boundary Containment System ranges from 4.2 to 16.8 years. Groundwater travel time during periods when Basin C was used as a recharge basin probably was 3 to 5 times shorter.

Three major pathways of contaminant migration have been identified in the Western Tier. Trichloroethylene is the primary contaminant detected in all pathways. Dibromochloropropane has been detected along one pathway. Groundwater contained in these pathways occurs in deposits of permeable sand and gravel. Hydraulic conductivity is large and hydraulic gradients are correspondingly small. Average linear velocity along these pathways is the highest of all pathways considered in this report. Groundwater travel time from the Motor Pool and Railyard Areas to the Irondale Containment System is

estimated to be between 0.7 and 2.7 years. The extent of contamination along this pathway by dibromochloropropane compares favorably with travel time calculations based on an effective porosity of 0.40. Groundwater travel time from the southern boundary of RMA to the Irondale Containment System is estimated to range from 1.1 to 4.3 years. Average linear velocities are similar along the Western Tier pathway and Off-Post Western Tier pathway.

1.0 INTRODUCTION

1.1 Purpose

The purpose of the Water Remedial Investigation is to present the U.S. Department of the Army's Remedial Investigation results for the Rocky Mountain Arsenal (RMA) on-post water media. This document is a formal Remedial Investigation product prepared in accordance with the Federal Facility Agreement (1989), the RMA Technical Program Plan (TPP), (Program Manager's Office, PMO, 1988, RIC#88131R01), and the June 1985 RI Guidance Document (U.S. Environmental Protection Agency, EPA). This report is one of the four Media Remedial Investigation reports (water, air, buildings and biota) and seven Regional Remedial Investigation Study Area Reports (SAR) prepared to fulfill the requirements of defining the nature and extent of contamination and completing a comprehensive Remedial Investigation for the On-Post Operable Unit of RMA as required by the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), the Superfund Amendments and Reauthorization Act (SARA), and the National Contingency Plan (NCP). The Water Remedial Investigation is a compilation, integration and interpretation of groundwater and surface water study results obtained from specific tasks designed to provide a comprehensive assessment of contaminant occurrence at the site. This report was prepared under contract numbers DAAA15-88-D-0024 and DAAK11-84-D-0016

1.2 Scope of Work

Recent Media Remedial Investigation efforts have focused on assessing air, biota, buildings, and water contamination at RMA. The Air Remedial Investigation (ESE, 1988c, RIC#88263R01) assessed airborne contaminant occurrences and established ambient air quality conditions for RMA. The Biota Remedial Investigation (ESE 1989a, RIC#89054R01) studied the presence and effect of potential contamination on plant and animal communities of RMA. The Buildings Remedial Investigation (Ebasco, 1988e, RIC#88306R02) carefully documented structure use history. This document, combined with a limited sampling effort, was used to assign contamination classifications to the structures. This report discusses contaminant occurrence and distribution within groundwater and surface water at RMA. Volume I presents an introduction to the project (Section 1); then describes the environmental setting (Section 2), nature and extent of contamination

(Section 3), and concludes with an assessment of contamination (Section 4). Volume II comprises supporting data for Volumes I and III. These supporting data are presented in Appendices A through E, and include geologic and hydrologic data, Task 44 data, chemistry data, and information pertaining to hydrochemical properties and hydrologic calculations. Volume III comprises Appendix F, which is a detailed description of geology, hydrology, contaminant distribution, and historical groundwater and surface water programs found in Volume I. Volume 4 contains Plates 1 through 20, which are referenced in Volumes I and III.

The Water Remedial Investigation assesses contaminant occurrence and distribution within the boundaries of RMA and in areas that are hydraulically downgradient. Hydraulically downgradient areas are northwest of RMA and are bounded on the northeast by Second Creek and on the northwest by the South Platte River. Therefore the study area described in this report is bounded by the southern and eastern boundaries of RMA, Second Creek and the South Platte River.

1.3 Methodology

In 1985 the Army created a separate office, the Program Manager's Office for the Rocky Mountain Arsenal Contamination Cleanup, specifically to deal with contamination problems at RMA. This office awarded contracts to two consultant teams, Environmental Science and Engineering (now Hunter/ESE) and Ebasco Services Incorporated to define the nature and extent of contamination at the site and to provide litigation support for the U.S. Department of Justice.

Task order contracts were developed for the consultant teams with general objectives to conduct an environmental program to define the nature and extent of contamination and select remedial action alternatives to mitigate contamination problems. Survey elements include the Remedial Investigation, Endangerment Assessment (EA), and Feasibility Study (FS). Twenty-three of the tasks involving water data acquisition or interpretation were utilized in the Water Remedial Investigation report. All tasks were completed in September, 1988.

1.4 Overview

RMA occupies over 17,000 acres in Adams County, Colorado (Figures 1.1 and 1.2) and is located approximately 10 miles northeast of downtown Denver. Stapleton International Airport extends into the southern border of the RMA (Figure 1.1). Land use along the remaining boundaries includes residential, light industrial manufacturing and agricultural. Residential population in the vicinity is concentrated to the west with a total of approximately 1.5 million within 15 miles of the RMA boundary.

Military History: RMA was established in 1942 by the U.S. Department of the Army as a manufacturing facility for the production of chemical and incendiary munitions. During World War II, chemical intermediate munitions, toxic products, and incendiary munitions were manufactured and assembled by the Army. From 1945 to 1950, stocks of Levinstein mustard were distilled, mustard-filled shells were demilitarized, and mortar rounds filled with smoke and high explosives were test-fired. Various obsolete ordnance were also destroyed by detonation or burning during this period.

In the early 1950's, RMA was selected to produce the chemical nerve agent GB (Sarin) under U.S. Army operations. The North Plants manufacturing facility was completed in 1953 and was used to produce agents until 1957. Munitions filling operations continuing until late 1969. The primary activities between 1969 and 1984 involved the demilitarization of chemical warfare materials.

Industrial Use History: Concurrent with military activities, industrial chemicals were manufactured at RMA by several lessees from 1947 to 1982. In 1947, portions of the site were leased to the Colorado Fuel and Iron Corporation (CF&I) and Julius Hyman and Company for chemical manufacturing of chlorinated benzenes, DDT, naphthalene, chlorine, and fused caustic. In late 1949, Julius Hyman and Company leased portions of the property previously covered by the CF&I lease. Shell Chemical Company acquired Julius Hyman and Company, in May 1952 and replaced Hyman as lessee. Shell Oil Company and its affiliate, Shell Chemical Company (collectively referred to as Shell), conducted manufacturing operations at the site until 1982, producing a variety of insecticides, herbicides, nematocides, and other compounds such as adhesives, anti-icers, and lubricating greases.

Compliance History: In May of 1974, diisopropylmethyl phosphonate and dicyclopentadiene were detected in surface water at the northern boundary. Later that year, the Colorado Department of Health (CDH) detected diisopropylmethyl phosphonate in a well north of the site and issued three administrative orders directed against Shell and the Army in April of 1975. These orders, commonly referred to as the "cease and desist orders", directed Shell and the Army to:

- o Take steps, as necessary, to cease and desist from all unauthorized discharges to the waters of the State;
- o File an application for a discharge permit;
- o Establish a groundwater surveillance program;
- o Maintain monitoring and sampling records; and
- o Report the results of monitoring to the State.

As a result of the cease and desist orders, a Contamination Control Program was established in 1974 to ensure compliance with Federal and State Environmental laws. A regional sampling and hydrogeologic surveillance program was initiated requiring quarterly collection and analysis of over 100 on-post and off-post surface water and groundwater samples. Since 1975, various programs have been implemented to monitor surface water and groundwater in accordance with operational and regulatory requirements.

Two lawsuits were filed in December 1983 as a result of the contamination at RMA. The first was brought by the State of Colorado against the United States of America and Shell for natural resource damages both on and off the site, and for response costs under CERCLA. The second was filed by the United States against Shell for response costs and for natural resource damage at RMA. The United States and Shell have entered into a Federal Facility Agreement and a Settlement Agreement that, among other things, establish procedures for assessment, selection, and implementation of response actions resulting from the release or threatened release of hazardous substances at or from the Arsenal and set forth the terms and conditions for payment of response costs by the Army and Shell.

1.5 Problem Definition

As a result of military and industrial activities on-post soils, groundwater and surface water became locally contaminated. With time, contaminants entered the groundwater and surface water systems and migrated on-post and to an extent off-post, creating a threat to shallow water wells immediately down-gradient of RMA boundaries. Soil and water contamination on-post resulted from routine disposal of waste effluent to lined and unlined basins, leaking sewer lines, and unintentional spills of raw materials, process intermediates, and end products from the manufacturing complexes. Disposal practices at RMA consisted of routine discharge of military and industrial waste effluents to lined and unlined evaporation basins and burial of solid wastes at various locations. Fluctuations in disposal volumes influenced the groundwater regime by artificially recharging the hydrogeological system, locally raising the water table (causing "mounding") and increasing contaminant transport velocities downgradient.

The number and concentration of contaminants present in RMA groundwater have changed through time. Factors contributing to these changes include variations in operational activities, procedures for handling materials and wastes, and physicochemical properties for contaminants. In addition environmental and climatic changes have changed the variety and concentration of contaminants.

1.6 Previous Investigations

In 1955, the Ralph M. Parsons Co. was contracted by the U.S. Army Corps of Engineers to undertake a study of waste disposal practices at RMA, to make recommendations based upon this study, and, to attempt to identify which chemical constituents, if any, in RMA liquid wastes discharged to unlined disposal ponds, were responsible for the crop damage occurring north of the Arsenal. The Parsons co. report issued in September 1955 recommended the sealing of 142 acres of existing unlined basins with catalytically blown asphalt. The original project for the sealing of liquid waste retention ponds developed by the Army in late 1955 and early 1956 called for the sealing of Basin C and the construction of a thirty-two acre sealed disposal pond in the area subsequently occupied by Basin F. However, because of wet and unstable conditions in Basin C in the Spring of 1956, the Army in June of the same year decided to build a single waste retention pond lined with catalytically blown asphalt; namely, Basin F. Basin F was constructed between

July and December 1956. Basin F began receiving liquid waste flows from the sump (B-1727) in the GB complex on October 27, 1956. For further information and supporting period documentation, see ESE, 1988a.

Significant studies conducted at RMA between 1955 and 1974 for the purposes of defining the hydrogeologic system and identifying toxic constituents(s) in the ground and surface water include:

- o L.R. Petri and R.O. Smith, Water Quality Division, Geological Survey U.S. Department of the Interior, Investigation of the Quality of Ground Water in the Vicinity of Derby, Colorado, August 1, 1956, CSD 017 0591-0684;
- o U.S. Army Corps of Engineers, Omaha District, Report on Ground Water Contamination, Rocky Mountain Arsenal, Denver, Colorado, September 1955;
- o E. Bonde, P. Urone, T. Walker, University of Colorado, Research on Phytotoxic Materials (sponsored by the U.S. Army Chemical Corps, Contract DA-05021-CML-10-092), Interim Reports, 1 July, 1 September, 1 December 1956; 1 January thru 1 December 1957; 1 January thru 1 December 1958; 1 January thru 1 May 1959; 1 May thru 31 May 1959; 1 June thru 30 June 1959; 1 July thru 31 July 1959; 1 August thru 31 August 1959; 1 September thru 30 September 1959; 1 October thru 31 October 1959; 1 November thru 30 November 1959; 1 December thru 31 December 1959; Final Report on Research on Phytotoxic Materials, 1 June 1956 thru 31 December 1959;
- o Robert L. Weintraub, U.S. Army Biological and Chemical Research Laboratory, Ft. Detrick, Md., "Toxicity of Rocky Mountain Arsenal Waste", Status Report, 25 May 1959;
- o Graham Walton, Engineering Section, Water Supply and Water Pollution, Research Branch, U.S. Department of Health, Education and Welfare, Public Health Aspects of the Contamination of Ground Water in South Platte River Basin in Vicinity of Henderson, Colorado, August 1959, November 2, 1959, RMA 062 0255-9282;
- o Public Health Service, Division of Water Supply and Pollution Control, South Platte River Basin Project, U.S. Department of Health, Education and Welfare, Ground Water

Pollution in the South Platte River Between Denver and Brighton, Colorado, December 1965, RIC 85007R02; and

- o U.S. Army Environmental Hygiene Agency, Water Quality Geohydrological Consultation No. 24-012-74, Rocky Mountain Arsenal 30 July - 3 August 1973, July 10, 1974, RAA 0230734-0821.

The first overall data assessment was performed by Geraghty & Miller, Inc., in 1981 (Stollar and van der Leeden, 1981, RIC#81293R05) and a site-wide hydrogeologic study was recommended as a result of this study. This recommended study was performed by the U.S. Army Corps of Engineers Waterways Experiment Station for the U.S. Army Toxic and Hazardous Materials Agency (USATHAMA).

U.S. Army Corps of Engineers Waterways Experiment Station studied groundwater flow directions and volumes in various geographical areas and identified areas where the shallow Quaternary age alluvium is in direct contact with underlying permeable sandstones of the Cretaceous to Tertiary age Denver Formation. This finding indicates that the alluvium and the Denver Formation are locally in hydrogeologic communication and that there is potential for contaminant transport between the units (May, 1982, RIC#82295R01).

In 1982, contaminant source control strategies and assessment of the associated remediation costs were developed in the Contamination Control Program. The report, titled "Selection of a Contamination Control Strategy for RMA" (RMACCPMT, 1983, RIC#83326R01), was generated by the RMA Contamination Control Program Management Team (RMACCPMT) in 1983 and delineated the procedures for the development of a contamination control strategy. The report documented the results of a two and one half year study of potential contamination control strategies that would ensure compliance with State and Federal statutes pertaining to the release of pollutants into the environment. The report also included an extensive technical review and analysis of migratory pathways of hazardous contaminants and their sources; an assessment of applicable environmental laws; development of corrective strategies within available technology; screening and evaluation of alternative strategies; and the selection of a preferred strategy.

A second report titled, "Decontamination Assessment of Land and Facilities at RMA" (RMACCMPT, 1984, RIC#84034R01) was developed by the Army for planning purposes. It

identified and classified over 150 potential contamination sites and provided a preliminary assessment of the extent, probable use, boundaries and possible contamination profile of the sites. This report was developed based upon personnel interviews and upon information contained in the first report. Study results were not field verified. The report also discussed environmental laws affecting decontamination activities and evaluated technical approaches for attaining decontamination.

To alleviate problems with off-post contamination migration, three groundwater treatment systems were installed at RMA; a pilot plant for the North Boundary Containment System, installed in 1978 and expanded in 1981; the Irondale Containment System installed in 1981; and the Northwest Boundary Containment System installed in 1984.

As a post-Remedial Investigation program to provide long term hydrogeologic information at RMA, the Comprehensive Monitoring Program was developed. This verification monitoring program was designed to provide both regional monitoring and site and/or source monitoring, as well as long-term hydrogeologic monitoring in both the on-post and off-post areas.

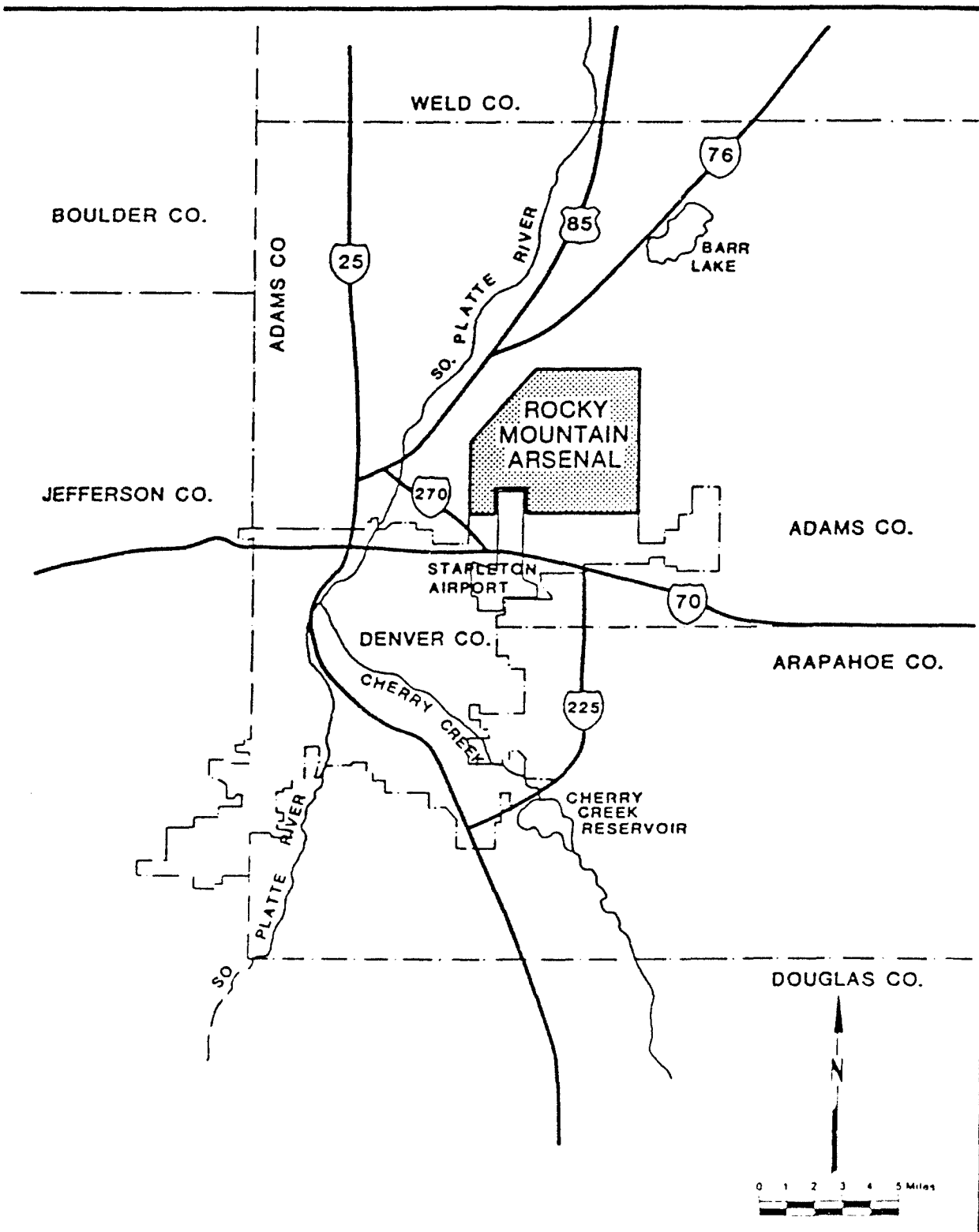


Figure 1.1
LOCATION MAP OF
ROCKY MOUNTAIN ARSENAL

SOURCE: Hunter/ESE, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal
Aberdeen Proving Ground, Maryland

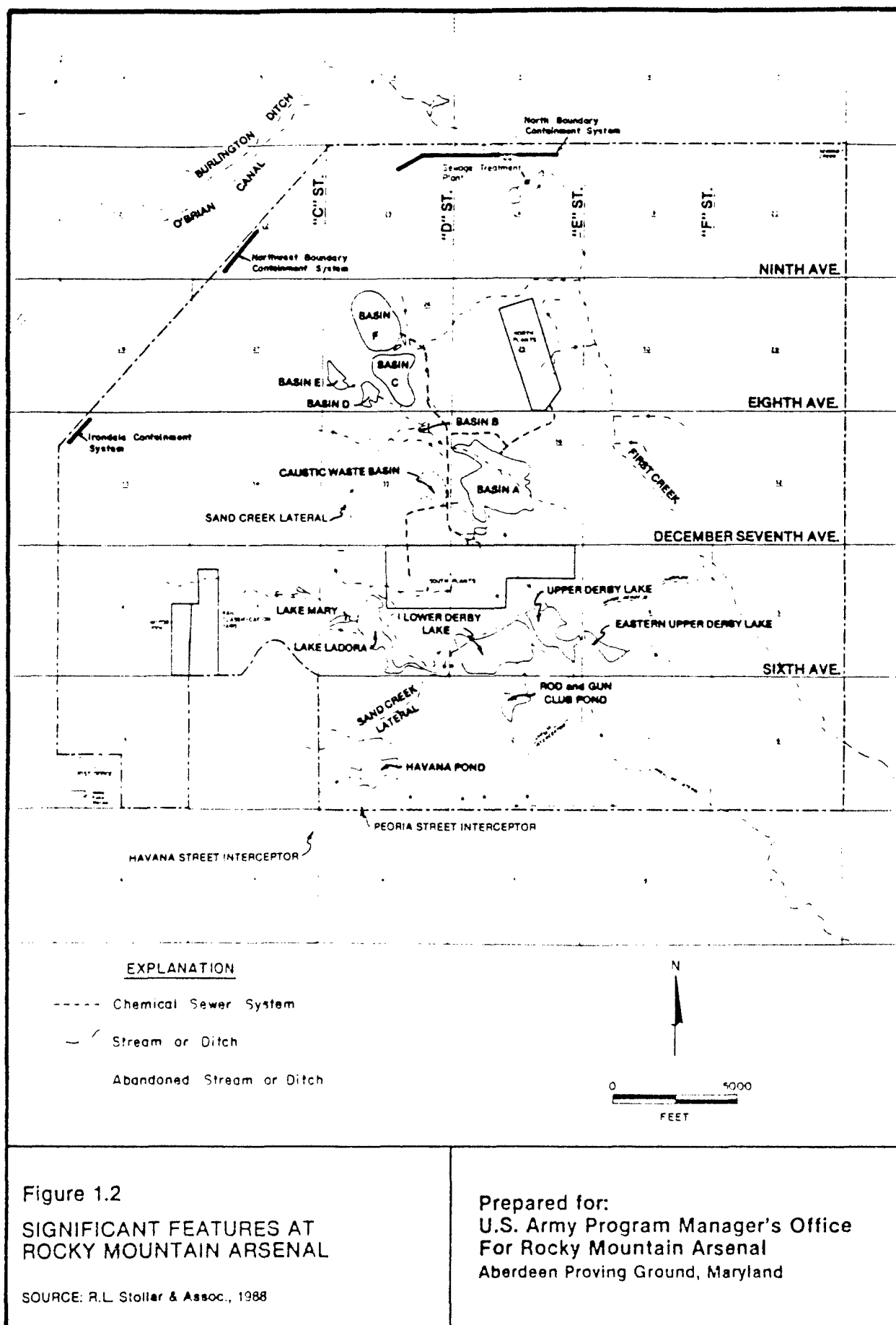


Figure 1.2

SIGNIFICANT FEATURES AT ROCKY MOUNTAIN ARSENAL

SOURCE: R.L. Stoller & Assoc., 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal
Aberdeen Proving Ground, Maryland

2.0 ENVIRONMENTAL SETTING

Contaminant distribution is controlled in part by the physiographic, geologic, and hydrologic characteristics of RMA and vicinity. The purpose of this section of the report is to describe these characteristics in sufficient detail to understand contaminant occurrence and migration. Subsequent sections of the report will describe contaminant occurrence and relate occurrence to physiographic, geologic, and hydrologic characteristics.

2.1 Physiography

RMA is part of the High Plains physiographic province and is characterized by gently rolling hills. The land surface slopes from southeast to northwest with a total change in altitude of 220 ft. Short grass prairie and disturbed grasslands predominate in the northern part of RMA while lakes, wetlands, and small areas of woodland are present in southern and eastern areas.

Average annual precipitation is approximately 15 inches with annual variations from approximately 7.5 to 23 inches. Approximately 50 percent of annual precipitation occurs between April and July. Snow accounts for approximately 30 percent of annual precipitation. Frequent summer thunderstorms result in substantial variations in precipitation over short distances. The combined potential evaporation and transpiration rate ranges from 24 to 30 inches per year (NOAA, 1957 to 1976). Large seasonal fluctuations in air temperature are common. The lowest recorded temperature was -30°F and the highest recorded temperature was 104°F (1936). Prevailing winds are from the south and southwest.

2.2 Surface Water Hydrology

Surface water at RMA flows within several small drainage basins that are tributaries of the South Platte River (Figures 1.1 and 1.2). The major drainages within RMA are First Creek and Irondale Gulch. Man-made structures including diversion ditches, lakes, and water retention basins have modified the natural drainage patterns. Culverts, sewers, and similar control structures also have been constructed.

First Creek drains an area of approximately 27 square miles upstream of RMA and approximately 12 square miles within the boundaries of RMA. First Creek discharges into O'Brian Canal approximately 0.5 miles north of RMA. Streamflow data for water years 1986 and 1987 indicate that mean monthly discharge of First Creek decreased from 82.2 acre-ft/mo where the stream enters RMA to 69.3 acre-ft/mo where it leaves RMA. Mean monthly discharge near the mouth of First Creek was 24.7 acre-ft/mo. There are no major diversions of surface water from First Creek. Streamflow in First Creek varies substantially during the water year. Extended periods with little or no flow are common.

The Irondale Gulch basin drains an area of approximately 11.5 square miles upstream of RMA and 6.5 square miles within the boundaries of RMA. Four lakes and several other impoundments within the basin are located on RMA. The Havana and Peoria Interceptors, North and South Uvalda Street Interceptors, and Highline Lateral deliver water from south of RMA to the lakes. Sand Creek Lateral diverts water from Havana Pond and Lower Derby Lake, collects additional runoff from the South Plants area, and flows north out of the Irondale Gulch drainage toward First Creek. Natural stream channels are poorly defined or lacking over most of the Irondale Gulch Basin partly as a result of moderate-to-high rates of soil infiltration. Streamflow statistics for man-made channels in the basin are summarized in Table 2.1.

Lakes, in downstream order at RMA, are Upper and Lower Derby Lakes, Ladora Lake, and Lake Mary. Ladora Lake and Lower Derby Lake were irrigation reservoirs prior to the construction of RMA. In 1942, the Army modified both reservoirs to enlarge their holding capacities and, in addition, built Upper Derby Lake. Lake Mary was constructed in 1960 as a recreational fishing area. Havana Pond and Rod and Gun Club Pond receive water from interceptor channels. The Rod and Gun Club Pond is connected to Lower Derby Lake via a ditch bisecting a lake sludge disposal site, although water levels are generally below the ditch bottom elevation. Storage capacity of the lakes varies from 60 acre-ft for Lake Mary to 970 acre-ft for Lower Derby Lake. Stage fluctuations have been monitored on a regular basis to aid in evaluating hydraulic interchange of surface water and groundwater.

Six basins, designated Basin A through Basin F, have been constructed for retention of process waste, wastewater, and storm runoff. Each basin is a natural topographic depression that has been modified by berms and other structures. Of the six basins, the

Table 2.1 Streamflow Statistics for Gaging Stations at RMA

Station	Mean Monthly (ac-ft/mo)	Maximum Instantaneous (cfs)	Minimum Instantaneous (cfs)	WY86 Total** (ac-ft)	WY87 Total** (ac-ft)
Peoria Intercept	11.7	230	0	92	211
Havana Intercept	98.4	677	0	1,088	1,276
Ladora Weir	8.4	16	0	76	141
South Uvalda	52.2	202	0.2	621	
North Uvalda	53.1	55	0	688	659
Highline Lateral	29.6	14.4	0	308	462
South First Creek	82.2	380+	0	1,006	1,003
North First Creek	69.3	213	0	1,068	733
South Plants Ditch	0.0	Trace	0	0	0
Basin A	0.8	5.6	0	9.6	10.4
First Creek at Hwy 2	24.7	23.2	0	*	413

ac-ft acre foot

ac-ft/mo acre foot per month

cfs cubic foot per second

* no data available

** WY Water Year defined as October 1 through September 30

Source: ESE, 1988.

largest storage capacities are associated with Basin A, Basin C, and Basin F. Basin F began receiving contaminated liquid wastes from the GB Plants sump (B-1727) on October 27, 1956. By the end of the first week in December 1956, the connecting sewer laterals from the South Plants Manufacturing area had been completed and all contaminated liquid wastes of RMA formerly discharged to Basin A were being set to Basin F. In December 1956, the Army began draining the accumulated ponded liquid wastes in Basin A to Basin F through a siphon-pipeline system connected to the GB Plant chemical sewer lateral at Manhole No. 5-1. This transfer was completed in September 1957, notwithstanding its temporary suspension in the Spring of 1957 while repairs to the liner of Basin F were being performed. Thereafter, until the summer of 1960, surface run-off accumulating in Basin A was drained to Basin F by means of a ditch and a sump, also connected to the GB Plant chemical sewer lateral at Manhole No. 5-1. For a short period in the Spring of 1957 (May 1 to June 20) the Army discharged contaminated liquid wastes into Basin A while repairs were being performed on the Basin F liner which had been damaged by wind induced wave action during the last week of April. Groundwater levels beneath Basin A are 1 to 4 ft below land surface.

Basin C originally collected overflow from Basin A. Water from Sand Creek Lateral was also diverted to Basin C. Infiltration of fresh water in Basin C probably affected the historical groundwater flow directions in the Basins C and F area. These effects are discussed in Section 4. Except for local runoff, Basin C has been dry since 1976.

Basin F was lined with 3/8 inches of asphalt and used for disposal of liquid waste at RMA from 1956 to 1978. Storage capacity of Basin F was 746 acre-feet. An interim response action (IRA) was initiated in 1988 at Basin F to remove liquid and solid wastes to safe, temporary storage and to prevent the further migration of any contamination still present in the area of the Basin until final remedial action is initiated. The project consists of transferring the residual liquid to temporary storage tanks and a lined and covered pond; stabilizing the sludges, asphalt liner and some of the subliner soil and placing the stabilized material in a double lined waste pile constructed within the basin; and placing a clay cap over the entire excavation basin to minimize infiltration. This IRA is scheduled to be completed by July 1989.

2.3 Geology

The groundwater system at RMA is part of the Denver structural basin that extends from Colorado into Western Nebraska, Kansas, and Eastern Wyoming. Strata in the Denver basin with usable quantities of potable water are the Fox Hills Sandstone, Laramie Formation, Arapahoe Formation, the Denver Formation, and the Dawson Arkose. The Dawson Arkose is present only in the southern part of the Denver basin and is absent at RMA. Unconsolidated alluvial and eolian deposits are at land surface throughout most of RMA. The bedrock immediately underlying these deposits is the Denver Formation.

Alluvial and eolian deposits at RMA locally attain thicknesses of 130 ft; however, the thickness of these deposits typically is much less. Several prominent paleochannels with alluvial thickness varying from approximately 50 to 130 ft have been identified in the erosional surface of the Denver Formation. Thickness of alluvial and eolian deposits in other areas generally is less than 50 ft. Areas with less than 20 ft of alluvial and eolian deposits are common. One of these areas, called the Basin A Neck in Sections 35 and 36, probably has an important influence on contaminant migration at RMA.

Older alluvial units located in areas along the South Platte River west and northwest of RMA generally consist of coarse-grained sand and gravel deposited during post-glacial periods. Eolian deposits and younger alluvial units are finer-grained than older alluvial units. Coarse-grained deposits generally occur within paleochannels while fine-grained material tends to blanket the entire area.

The Denver Formation underlying the alluvium consists of interbedded claystones, siltstones, sandstones, and organic-rich (lignitic) intervals. Water-bearing layers of sandstone and siltstone occur in irregular beds that are dispersed within relatively thick sequences of relatively impermeable material. Individual sandstone layers commonly are lens shaped and range in thickness from a few inches to as much as 50 ft. Reliable correlation of individual sandstone layers between wells is generally good in areas such as South Plants and Basin A where a thick lignite bed (LA) is present and provides a recognizable marker horizon. Correlations through other areas of RMA are more tenuous. Lignitic beds typically vary in thickness from 0 to 13 ft, are more continuous laterally than sandstone layers, and commonly are fractured. Low permeability volcanoclastic

material is present in the upper part of the Denver Formation. The Denver Formation is 200 to 500 ft thick at RMA.

Stratigraphic zones within the Denver Formation have been identified on the basis of relatively continuous lignitic marker beds (Figure 2.1). Each zone consists of discontinuous sandstones separated by claystone. The interval of volcanoclastic material is identified as a separate stratigraphic zone. Data to map geologic characteristics of each zone are most common where the zone is shallow. Sandstone units in shallower zones vary in thickness from near 0 ft to greater than 50 ft. Sandstone units generally trend north to south.

Bedding planes in the Denver Formation dip approximately 1° to the southeast. Because of this, relatively older stratigraphic zones subcrop against alluvium in northwestern parts of RMA, with progressively younger zones subcropping toward the southeast. Evidence for folding or faulting in the Denver Formation at RMA is inconclusive.

2.4 Unconfined Flow System

Groundwater at RMA occurs under both confined and unconfined conditions. Water in bedrock typically is under confined conditions while water in unconsolidated surficial deposits typically is under unconfined conditions. Exceptions occur in areas where bedrock units are exposed at land surface or overlying unconsolidated deposits are unsaturated. Where these conditions occur, water in shallow bedrock is unconfined.

The Unconfined Flow System includes saturated alluvium, eolian deposits and subcropping parts of the Denver Formation where lithologic data indicate the presence of sandstone or other relatively permeable material. In areas where alluvial and eolian deposits are unsaturated, the Unconfined Flow System consists solely of sandstone and fractured or weathered rock within the shallow parts of the Denver Formation. This definition does not preclude lateral flow between alluvium and permeable material in subcropping Denver Formation. However, rates of flow within these parts of the Denver Formation may be substantially different from rates of flow in the alluvium due to differences in hydraulic conductivities between these units.

The bottom of the Unconfined Flow System is delineated by the following criteria. Where no sandstone of the Denver Formation subcrops, the bedrock-alluvium interface is the bottom of the Unconfined Flow System. If subcropping sandstone is present, the sandstone in the area of subcrop is included as part of the Unconfined Flow System. If alluvium is unsaturated or absent, the bottom of the Unconfined Flow System is defined by the depth of weathered rock in the Denver Formation. Based on these criteria, the Unconfined Flow System extends throughout RMA and vicinity.

The saturated thickness of the Unconfined Flow System varies from less than 10 ft to approximately 70 ft (Figure 2.2). Thickness is greatest in paleochannels and typically varies from 20 to 50 ft. Thickness beneath Basins A-F and South Plants typically is 20 ft or less. Large areas with thickness less than 7 ft have been identified in Sections 20, 26, and 29.

2.4.1 Hydraulic Properties

The Unconfined Flow System has been divided into seven hydrogeologic units on the basis of lithologic descriptions and aquifer test results (Figure 2.3). Six of the hydrogeologic units are located within unconsolidated Quaternary deposits. Unconfined parts of the Denver Formation are grouped as the seventh unit. Aquifer test results were used to estimate typical values of hydraulic conductivity for each hydrogeologic unit (Table 2.2). A complete lithologic description of each hydrogeologic unit is given in Appendix F.

Hydraulic conductivity of unconfined Denver Formation is one to two orders of magnitude smaller than the eolian unit and two to three orders of magnitude smaller than alluvial gravel and coarse-grained sand units. Estimates of hydraulic conductivity in the Denver Formation range from 0.03 to 3 ft/d. Estimates in the eolian unit range from 10 to 100 ft/d and estimates in gravel and coarse-grained sand units range from 60 to 3,000 ft/d. Estimates of hydraulic conductivity were obtained from results of 16 aquifer tests with observation wells, 9 aquifer tests without observation wells and 75 slug tests.

Specific yield estimates obtained from aquifer test results correlate qualitatively with hydrogeologic units. In eolian and fine-grained alluvial units, specific yield estimates

Table 2.2 Hydraulic Conductivity Estimates for Hydrogeologic Units of the Unconfined Flow System

Hydrogeologic Unit and Symbol	Hydraulic Conductivity	
	Best Estimate (ft/day)	Range (ft/day)
Terrace gravel (QT)	900	300 to 3,000
Paleochannels in terrace gravels (QA1)	900	300 to 3,000
Gravel-filled paleochannels in eolian deposits (QA2)	300	100 to 1,000
Silty terrace gravels and coarse sand (QA3)	200	60 to 600
Paleochannels without gravel in eolian deposits (QA4)	100	30 to 300
Eolian deposits (QE)	60	10 to 100
Unconfined Denver Formation (TK _d)	0.3	0.03 to 3

range from 0.01 to 0.05. Specific yield estimates in coarser material typically are 0.23 to 0.25. Aquifer-test results in the Denver Formation have not provided reliable estimates of specific yield.

2.4.2 Potentiometric Surface

Potentiometric surface data (Figure 2.4) obtained in 1987 indicate that groundwater in the Unconfined Flow System generally flows toward the north and northwest. Spatial variation in hydraulic gradients can be attributed to variations in saturated thickness, hydraulic conductivity, and locations of recharge and discharge. Where saturated thickness is small, hydraulic gradients are also influenced by the configuration of the bedrock surface. In areas where the Unconfined Flow System is primarily alluvium, hydraulic gradients vary from approximately 0.002 to 0.009 ft/ft. In areas where the Unconfined Flow System is primarily Denver Formation, hydraulic gradients are generally larger (0.007 to 0.019 ft/ft).

As a result of the 10 ft contour interval selected for mapping the potentiometric surface, some detail has been lost. More detailed maps are available within Study Area Reports and other more site-specific documents. Flow paths inferred from Figure 2.4 are generally correct; however, more detailed maps must be used in areas of rapidly diverging flow. More detailed maps also show several groundwater mounds in parts of the Unconfined Flow System that correspond to unconfined Denver Formation. When total head change across these mounds is less than 10 ft, the mound may not appear on Figure 2.4. Examples of low magnitude groundwater mounds occur in the area of unsaturated alluvium northwest of Basin F and north of Basin A.

Hydraulic gradients in the Unconfined Flow System are small in areas where saturated thickness and hydraulic conductivity are large. Small hydraulic gradients (0.004 ft/ft) include the RMA Western Tier and the South Platte River. Other areas with small hydraulic gradients are near First Creek (0.006 ft/ft), south-central parts of RMA (0.009 ft/ft), and between the RMA northern boundary and the South Platte River (0.008 ft/ft).

Hydraulic gradients in the Unconfined Flow System generally are large in areas where hydraulic conductivity is relatively small, or where saturated thickness is small and the elevation of the bottom of the Unconfined Flow System changes substantially. These

conditions exist northwest of Basin F, in parts of Sections 27, 34 and 35, and in areas where flow in the Unconfined Flow System occurs through rocks of the Denver Formation.

A small hydraulic gradient (0.002 ft/ft) occurs from Basin F to the RMA northern boundary. Saturated thickness generally is small (less than 20 ft) and a substantial part of the Unconfined Flow System in this area consists of the Denver Formation. Reasons for the small gradient include a probable small quantity of water moving between Basin F and the RMA northern boundary, and hydraulic head control near the RMA northern boundary where water flowing from the vicinity of Basin F mixes with a larger volume of water flowing beneath First Creek. Installation and operation of the North Boundary Containment System also has influenced the hydraulic gradient from Basin F to the northern boundary of RMA.

Water levels beneath the South Plants area indicate the presence of a groundwater mound, and water flows radially away from this groundwater high beneath South Plants. The mound has existed since 1957 and perhaps earlier. The Unconfined Flow System beneath the South Plants area is predominately claystone and volcanoclastic material of the Denver Formation and has relatively small hydraulic conductivity. Where saturated, surficial deposits are silt and clay with small hydraulic conductivity. The Unconfined Flow System in areas adjacent to the mound consists of material with larger hydraulic conductivity. Assuming uniform recharge from precipitation in the South Plants and adjacent areas, the spatial differences in hydraulic conductivity are sufficient to cause water table mounding.

Recharge beneath South Plants has been enhanced in the past and contributed substantially to the height of the groundwater mound. Enhanced recharge occurred as a result of leaking pipes and sewer lines, collection of water in low-lying areas and other activities within the South Plants area. A major leak in the sewer system was identified and corrected in 1980. Water levels beneath South Plants have declined 1 to 2 feet since 1982.

2.4.3 Water Level Fluctuations

Historical water level fluctuations have been large in the vicinity of Basin C. Elsewhere, historical water level fluctuations have been small. Fresh water was stored in Basin C during the late 1950's. Water level data collected during 1957 (Smith, et al., 1963

RIC#84324R02) indicate that hydraulic heads beneath Basin C and Basin F were 20 to 30 ft higher than present-day heads. Basin C also was used extensively for storage of fresh water from 1969 through 1975. Water level data for this period were not available. Water level data for the composite period 1955 through 1971 (Konikow, 1975, RIC#84324M01) show water-levels beneath Basin C, Basin F and Basin A Neck were approximately 10 ft higher than present-day water levels. Basin C has not been used extensively since 1976 and water level data collected since 1978 reflect the present-day potentiometric surface generally with deviations of less than 5 ft.

The present-day water level beneath Basin C, Basin F, and adjacent areas is at or slightly below the contact between Denver Formation and overlying alluvium. Relatively small increases in water level would cause the alluvium to become saturated. Because hydraulic conductivity of the alluvium probably is one to two orders of magnitude larger than hydraulic conductivity of the Denver Formation, flow paths and travel times for contaminant migration may be substantially lower today than when Basin C contained water.

Seasonal water level fluctuations as large as 7 ft have been measured near South Plants between 1982 and 1986. Seasonal fluctuations elsewhere at RMA tend to be less than 2 ft. The magnitude of changes in the South Plants area may be a reflection of smaller hydraulic conductivity and specific yield beneath South Plants compared with adjacent areas, or it may be a reflection of changes in recharge.

2.4.4 Recharge and Discharge

Recharge to the Unconfined Flow System occurs as infiltration of precipitation and irrigation, seepage from lakes and streams, and seepage from reservoirs, canals and buried pipelines. Water also enters the Unconfined Flow System by underflow of groundwater from areas south and east of the study area. Water in transmissive strata of the Denver aquifer flows laterally into the Unconfined Flow System where the elevation of the bedrock varies appreciably in a short distance and the transmissive strata subcrop. Rates of recharge vary seasonally, have caused relatively minor changes in water levels and groundwater flow paths, and will not be discussed in detail.

Recharge rates within the study area (Table 2.3) have been tabulated from a number of investigations during the period 1981-1987. Descriptions of each recharge component are given in Appendix F. The recharge rates shown in Table 2.3 were used as initial estimates in developing a regional model of flow in the Unconfined Flow System. The model is described in Section 4.3 of this report.

Discharge from the Unconfined Flow System occurs as seepage to Lake Ladora, Lake Mary, Rod and Gun Club Pond, and the South Platte River. Additional groundwater discharge occurs by evapotranspiration from the water table in areas such as Upper Derby Lake where the water table is within 5 ft of the land surface. Water in the Unconfined Flow System flows vertically into the underlying Denver aquifer. Vertical flow probably occurs through fractures in areas where the subcropping strata are predominantly shale or claystone. Estimates of discharge rates to Lake Ladora, Lake Mary, and Rod and Gun Club Pond were obtained by calculating water budgets for each lake. Total discharge to these three lakes is estimated to vary from 82 to 385 acre-ft/yr. Estimates of groundwater discharge to the South Platte River, based on calculations with Darcy's law, are sensitive to uncertainty in estimates of hydraulic gradients and hydraulic conductivity. Discharge estimates range from 37,600 to 56,600 acre-ft/yr.

2.5 Denver Aquifer

The Denver aquifer in the vicinity of RMA consists of parts of the Denver Formation where water is under confined conditions. Generally, confined conditions are observed within permeable sandstone or lignite that is separated from permeable material of the Unconfined Flow System by relatively impermeable shale or claystone. Because upper stratigraphic intervals of the Denver Formation are included in the Unconfined Flow System where water is unconfined, there is no direct correlation between rock of the Denver aquifer and stratigraphic intervals of the Denver Formation. The bottom of the Denver aquifer is delineated by 30 to 50 ft of claystone and shale, informally called the Buffer Zone, that separates the Denver from the underlying Arapahoe aquifer. The Arapahoe formation underlies RMA at a depth of approximately 250 to 400 feet below ground surface (May, 1982, RIC#82295R01).

Table 2.3 Estimated Recharge to the Unconfined Flow System Within the Study Area

Source of Recharge	Estimated Recharge (acre-feet/year)
Precipitation	630
First Creek, on-post	300
First Creek, off-post	316
Basin A	10 to 20
Basin B	4
Basin C	2
Basin D	50
Basin E	0
Sewage Treatment Plant	0
Lower Derby Lake	480
Upper Derby Lake	unknown
Havana Pond	1,300
Uvalda Interceptor	360
Rail Classification Yard	13
Sand Creek Lateral	20
Fulton Ditch	4,020
Burlington Ditch	5,300
O'Brian Canal	10,400 to 15,800
Highline Lateral	489 to 900
North Bog	190
Irrigation	6,750
Lateral Flow at Study Area Boundary	5,000
Denver Formation	600
TOTAL	36,300 to 42,100

2.5.1 Hydraulic Properties

Hydraulic conductivity estimates vary spatially and reflect variations in lithology. Hydraulic conductivity of the shale and claystone matrix is small; probably 10^{-2} to 10^{-4} ft/d. In contrast, hydraulic conductivity for sandstone in the Denver aquifer has been estimated by slug-test analyses to range from 0.03 to 4 ft/d. Values less than 0.3 are typical of silty sandstone. Values from aquifer tests range from 1.1 to 7.7 ft/d. Estimates of hydraulic conductivity for lignitic beds that have been fractured are not available. However, flow model analyses indicate that hydraulic conductivity of lignitic beds may be an order of magnitude greater than hydraulic conductivity of sandstone.

Contaminant migration in the Denver aquifer depends on the occurrence of interconnected sandstone lenses and fractured lignitic beds. Thickness and areal extent of sandstone in stratigraphic zones of the Denver Formation is described by a series of maps in Appendix F. Sandstone varies in thickness from a few inches to 50 ft. The maps identify thicker areas of sandstone that trend generally south to north with substantial deviations in trend within each stratigraphic zone.

2.5.2 Distribution of Hydraulic Head

Head in the Denver aquifer decreases with depth at most locations in the vicinity of RMA. Increasing head with depth has been observed at relatively few isolated locations (Appendix F, Figure 2.4-11). Decreasing head with depth at RMA is consistent with regional potentiometric surface maps for deep aquifers in the Denver basin (Robson, 1987). Prior to 1885, head increased with depth in deep aquifers beneath RMA and heads in the Denver, Arapahoe, and Laramie-Fox Hills aquifers were large enough to cause flowing wells in the valley of the South Platte River. Groundwater withdrawals from 1885 to the present have caused water level declines greater than 300 ft in the Denver area. As a result, the vertical gradient at RMA currently is downward.

Hydrogeologic cross sections constructed from the South Plants area to the RMA northwestern boundary (Plate 1) and to the RMA northern boundary (Plate 2), indicates that there is potential for groundwater flow toward the northwest as well as downward potential. Similar results are obtained by constructing potentiometric surface maps for stratigraphic zones in the Denver aquifer (Figures 2.5 through 2.10). While these maps

indicate potential for flow, rates of flow are also dependent on hydraulic conductivity. The smaller hydraulic conductivity of claystone relative to sandstone likely restricts vertical flow to some degree while enhancing lateral flow.

2.5.3 Recharge and Discharge

Recharge to the Denver aquifer occurs by vertical leakage from the overlying Unconfined flow System in areas where the subcropping bedrock is predominantly shale or claystone. Head differences between the Unconfined Flow System and confined sandstone strata of the Denver aquifer indicate a potential for downward leakage. Rates of leakage per unit area are small but probably are enhanced by movement through fractures. Rates of leakage are a function of head difference and vertical hydraulic conductivity. A single estimate of vertical hydraulic conductivity (4.1×10^{-5} ft/d) is available from a pumping test conducted near the North Boundary Containment System. Recharge to the Denver aquifer also occurs by underflow from areas south and east of RMA.

Discharge from the Denver aquifer occurs by lateral flow into the Unconfined flow System where transmissive strata of the Denver aquifer subcrop and the elevation of the bedrock varies appreciably over a short distance. Discharge from the Denver aquifer also may occur by leakage to the Arapahoe aquifer. No production wells obtain water from the Denver aquifer at RMA.

Recharge and discharge of water in the Denver aquifer is controlled on a local scale by variations in hydraulic conductivity, the potentiometric surface of the Unconfined Flow System, and bedrock surface. Locations where sandstone or other permeable material are in contact with the Unconfined Flow System are likely areas for local recharge and discharge. Recharge and discharge probably occur on a local scale where the elevation of the bedrock surface varies appreciably in a short distance. For example, within the cross section shown in Plate 1, localized recharge through shale probably occurs in Section 35 where head gradients indicate downward flow. The recharge water moves perpendicular to the lines of equal potential through Denver sands A, 1U, and 1. Localized discharge to the Unconfined Flow System probably occurs where Denver sand subcrops near the boundary between Section 26 and Section 35. A similar local condition probably occurs in Section 27. The groundwater mound in the Unconfined Flow System near the South Plants area probably functions as an area of recharge to the Denver aquifer.

Quantitative estimates of recharge and discharge rates in the Denver aquifer are not available. Because recharge and discharge in the Denver aquifer are closely related to variations in hydraulic conductivity and the potentiometric surface of Unconfined Flow System and bedrock surface, reliable estimation probably would require cross-sectional or three-dimensional flow modeling in areas of suspected recharge and discharge.

2.6 Surface Water - Groundwater Interaction

Mass balance calculations have been used to estimate groundwater recharge and discharge beneath lakes. Water entering and leaving each lake was measured. Lake evaporation was estimated on the basis of pan evaporation data collected at Cherry Creek Dam south of Denver. Changes in lake storage were estimated from lake level data and stage-volume relations. The residual of the mass balance calculation was estimated to be groundwater recharge or discharge. Water level data for the Unconfined Flow System were compared to lake level data in order to verify mass balance calculations. A description of the analysis for each lake is given in Appendix F, Section 2.0.

Upper Derby Lake loses water to the Unconfined Flow System at the rate of 3.5 acre-ft/mo when the lake contains water, but functions as a groundwater discharge area when the lake is empty. Groundwater discharge at the rate of 2.5 acre-ft/yr occurs by evapotranspiration from the water table. The water table generally is within two feet of the lake bottom.

Lower Derby Lake functions as a groundwater recharge area. Lake losses averaged 39.7 acre-ft/mo during water years 1986 and 1987.


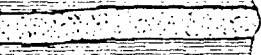














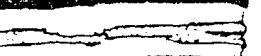

Lake-aquifer head relations indicate that both Lake Ladora and Lake Mary receive groundwater in upstream areas and lose water in downstream areas. However, mass balance calculations indicate net losses of water for both lakes. Net groundwater recharge is estimated to be 14 acre-ft/mo from Lake Ladora and 1.4 acre-ft/mo from Lake Mary.

Mass balance calculations for Havana Pond indicate that virtually all water entering the pond becomes groundwater recharge. Average recharge is estimated to be 108.3 acre-ft/mo. Water level data are consistent with this estimate.

Basins A through F exchange water with the Unconfined Flow System at very low rates. A detailed discussion of each basin is given in Appendix F.

Historically, groundwater recharge in the vicinity of Basin A through F was different from present conditions. Konikow (1977) estimated rates of groundwater recharge during four periods from 1943 through 1972. The estimates were obtained as part of flow-model calibration. From 1943 through 1956 total recharge from Basins A, B, C, D, and E was estimated to be 0.88 ft³/s. From 1957 through 1960 Basins A, B, D, and E were treated as empty and recharge from Basin C was estimated to be 1.08 ft³/s. From 1961 through 1967 recharge from Basins B, C, D, and E was estimated to be 0.42 ft³/s. From 1968 through 1972 recharge from Basin C was estimated to be 1.08 ft³/s while Basins A, B, D, and E were assumed to be empty. A water budget analysis of Basin C for the years 1969 through 1975 (MKE, 1988, written communication) indicates that average recharge from fresh water storage was approximately 0.95 ft³/s.

Streamflow loss-and-gain studies have been used to estimate stream-aquifer relations at RMA. Results have been compared with stream-aquifer head relations where possible. Calculations indicate that Uvalda Interceptor loses approximately 30 acre-ft/mo. Highline Lateral is estimated to lose 75 acre-ft/mo. First Creek loses approximately 2.9 acre-ft/mo within the boundaries of RMA and an additional 44.6 acre-ft/mo north of the RMA. These estimates represent averages during the 1986 and 1987 water years. Actual values for a given time deviate substantially in response to changes in stream discharge and aquifer head. During periods of negligible streamflow, First Creek north of the RMA boundary gains groundwater at a small rate (0.06 cfs).

SYSTEM	ZONE & THICKNESS		LITHOLOGIC DESCRIPTION	
QUATERNARY	Alluvium	(0-130')		Gravels, silty sands, sandy silts, and clays; laterally variable
CRETACEOUS - TERTIARY DENVER FORMATION	B	0-25' (0-19')		B Sandstone and claystone
	Volcanic-clastic	0-50'		Volcaniclastic material and laterally equivalent claystone and sandstone
	A	0-75'		<div style="display: flex; align-items: center;"> <div style="margin-right: 10px;"> AU (0-13') AM (0-20') AL (0-20') </div> <div style="margin-right: 10px;"> AS (0-46') </div> <div> Sandstone, claystone, and lignite </div> </div>
	Lignite A	0-11'		
	IU	0-40' (0-36')		
	Lignite B	0-12'		
	1	0-60' (0-54')		
	Lignite C	0-13'		
	2	0-55' (0-41')		
	Lignite D	0-13'		
	3	0-45' (0-33')		
	4	0-50' (0-36')		
	5	0-25' (0-19')		
	6	to 30' (to 23')		
	7	to 30' (to 20')		
	8	to 40' (to 27')		
	9	to 20' (to 5')		

Note: Thicknesses are in feet, but sandstone thickness shown in parentheses.

Figure 2.1

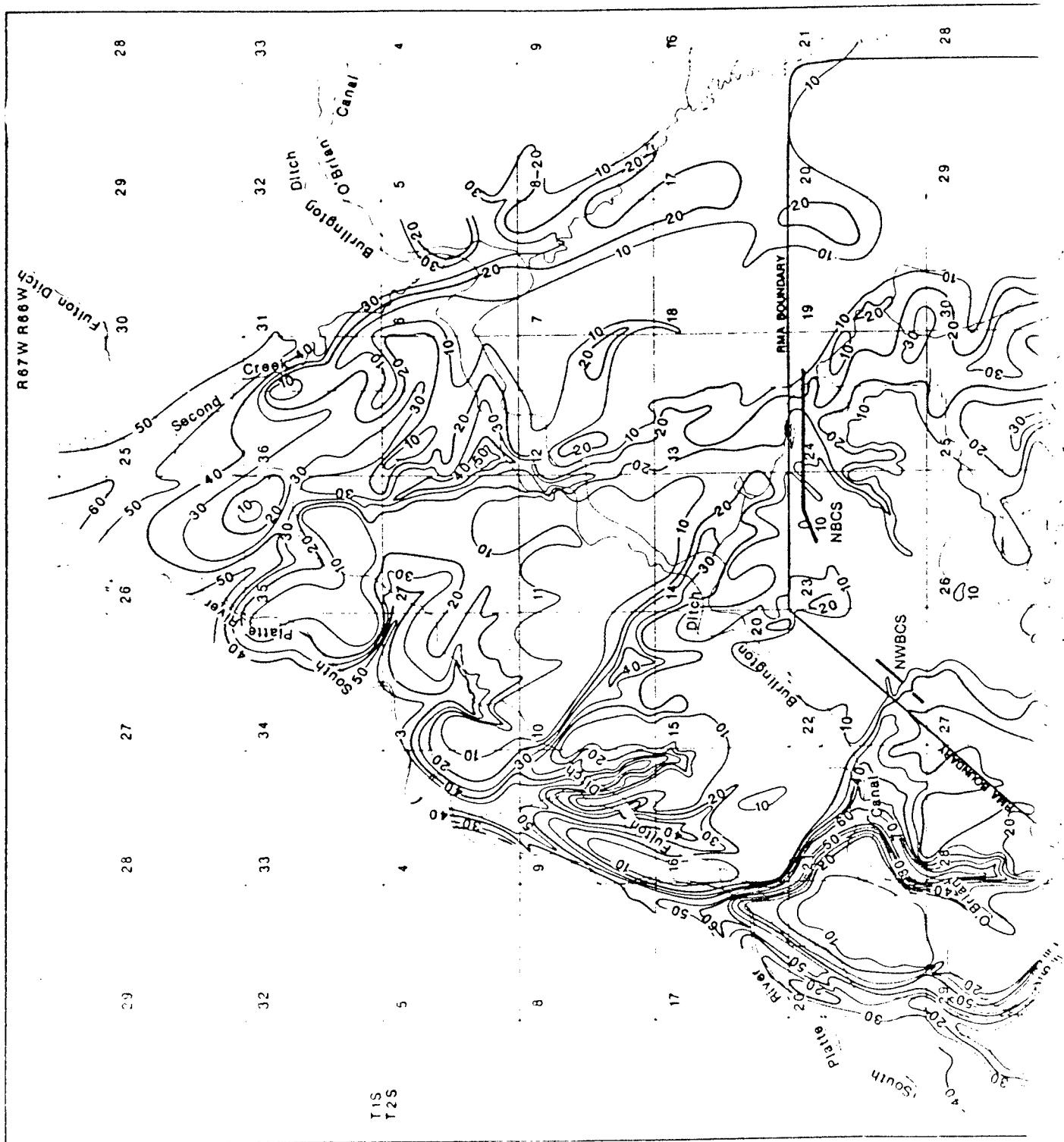
MA DENVER FORMATION
STRATIGRAPHIC COLUMN

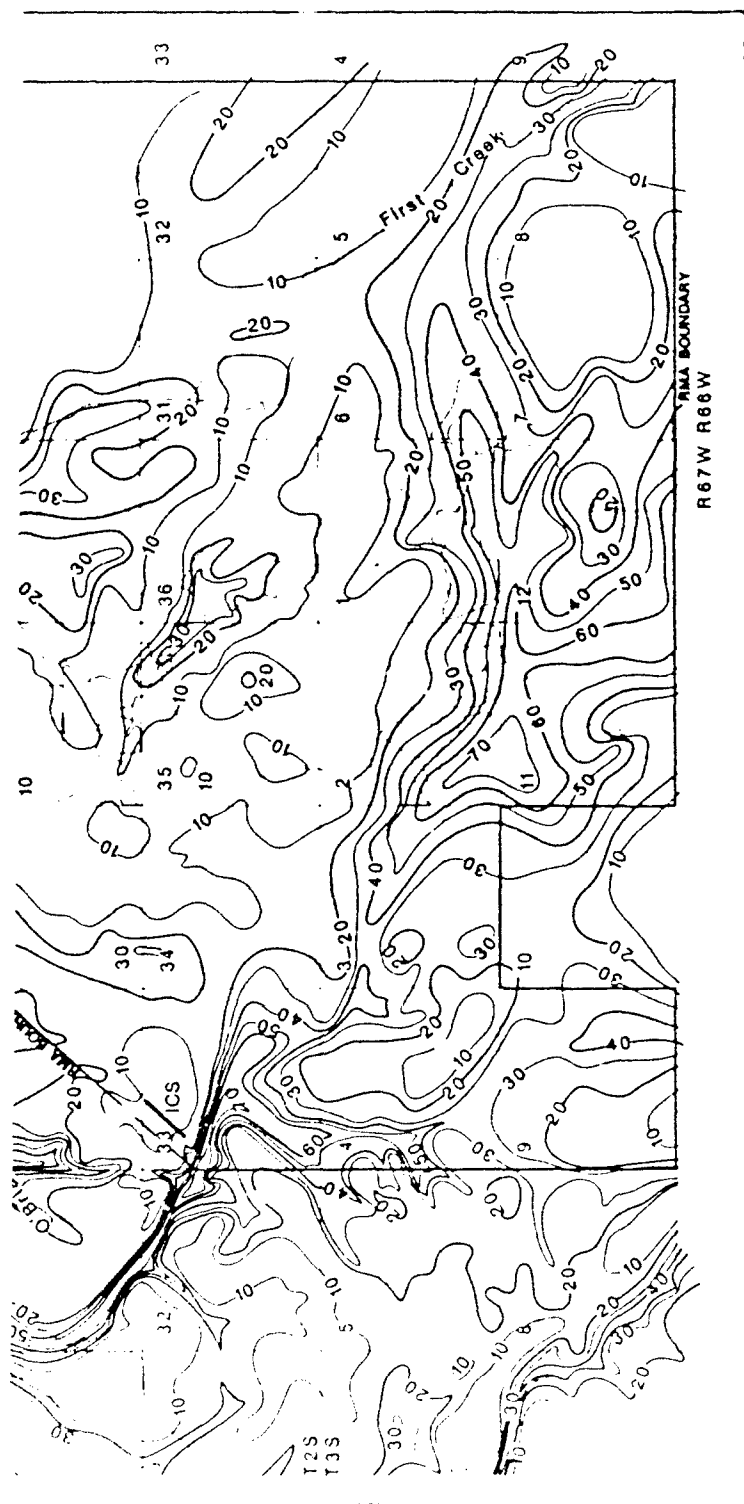
SOURCE: HLA, Hunter-ESL, 1988

Prepared for:

U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland





EXPLANATION

Contour Interval Equals 10 Feet
Elevations in Feet
Datum Mean Sea Level

ICS Ironclad Containment System
NBCS North Boundary Containment System
NWBCS Northwest Boundary Containment System

Figure 2.2

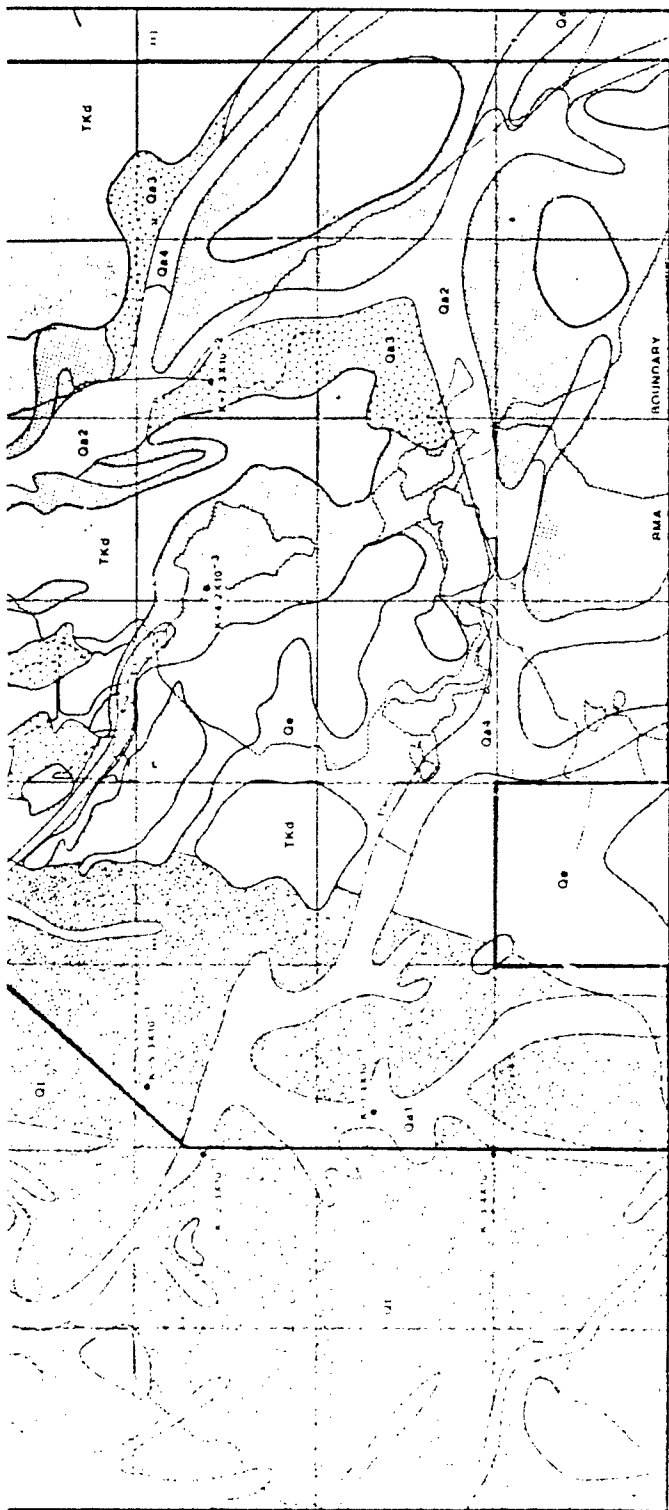
SATURATED THICKNESS MAP FOR UNCONFINED FLOW SYSTEM

SOURCE: MIA, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland





EXPLANATION

- Qa1 Silty Terrace Gravel And Coarse Sand
K = 8x10⁻² Range = 2x10⁻² - 10⁻¹
- Qa2 Paleochannels In Eolian (W/Gravel)
K = 5x10⁻³ Range = 10⁻³ - 10⁻¹
- Qa3 Eolian Deposits
K = 2x10⁻² Range = 4x10⁻³ - 10⁻¹
- Qa4 Denver Fm/Dry Alluvium
K = 1x10⁻⁴ Range = 10⁻⁵ - 10⁻³
- Qe Alluvial Aquifer Pumping Tests
- TKd
- Qs

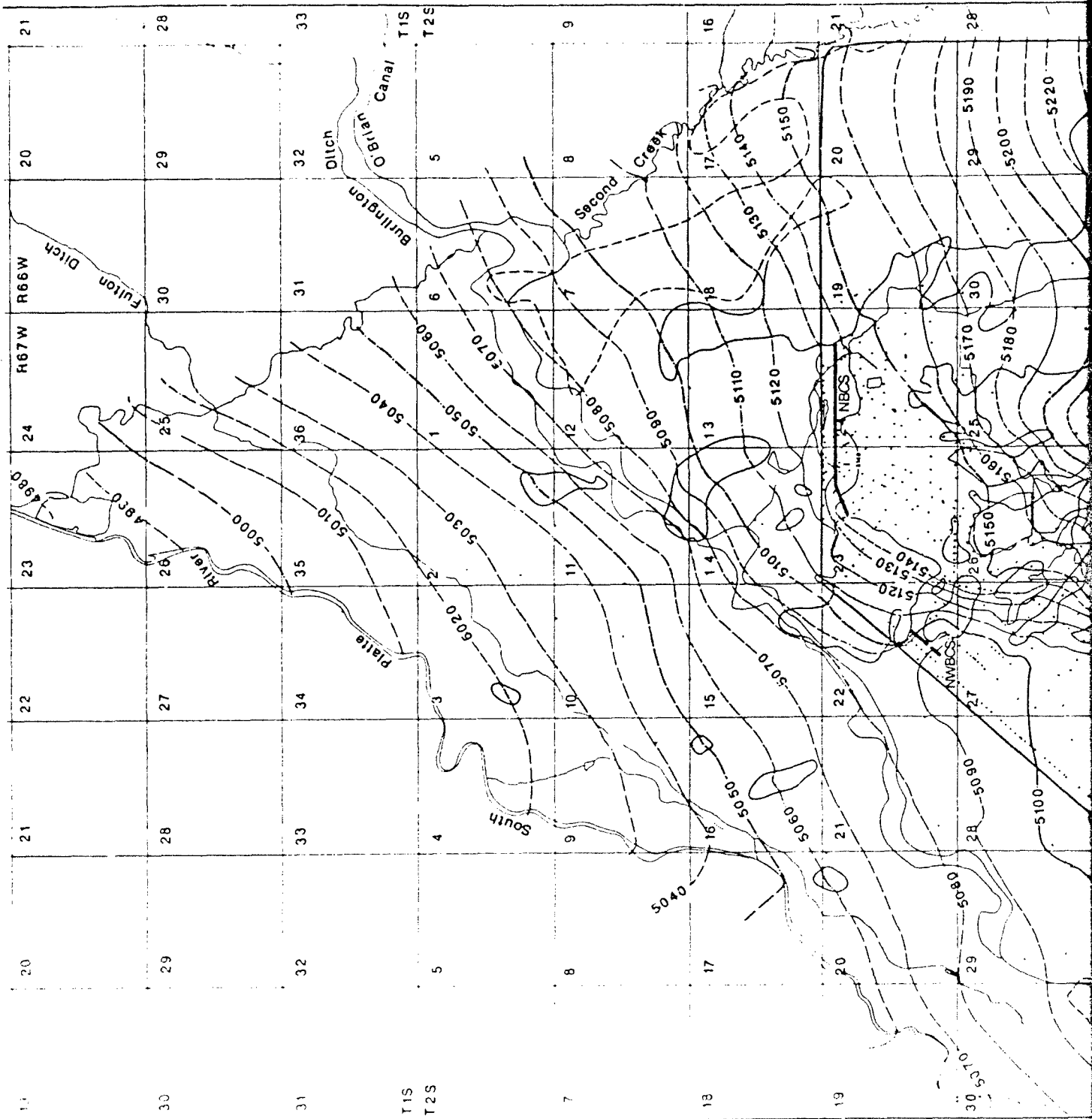
Figure 2.3

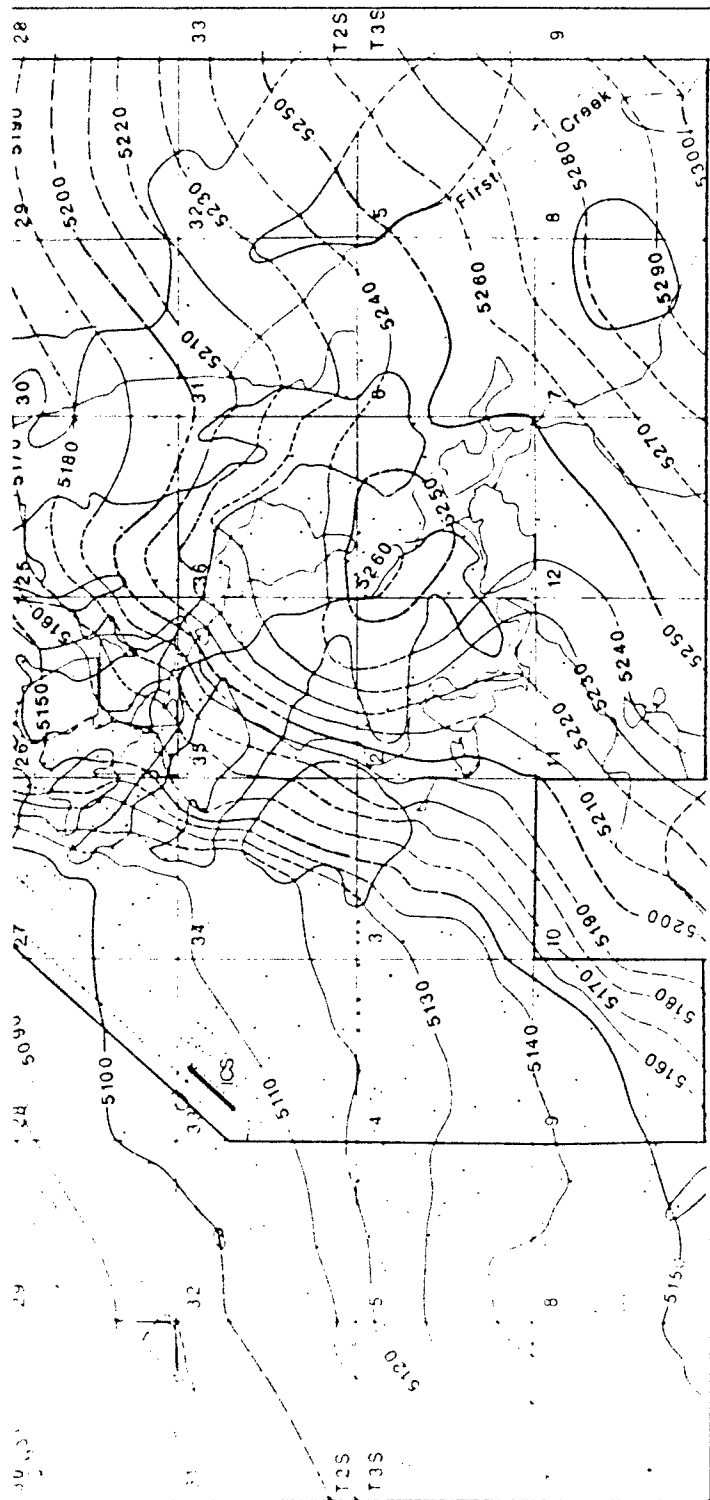
HYDRAULIC CONDUCTIVITY MAP FOR UNCONFINED FLOW SYSTEM

DAVID E. HARRIS, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland





EXPLANATION

Contour Interval Equals 10 Feet

Elevations in Feet

datum Mean Sea Level

Unsaturation Alluvium

Inferred Contour

Interpreted Contour

▲ Groundwater Monitoring Well

ICS Irondale Containment System

NBCS North Boundary Containment System

NWBCS Northwest Boundary Containment System

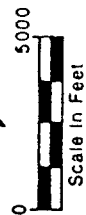
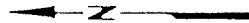


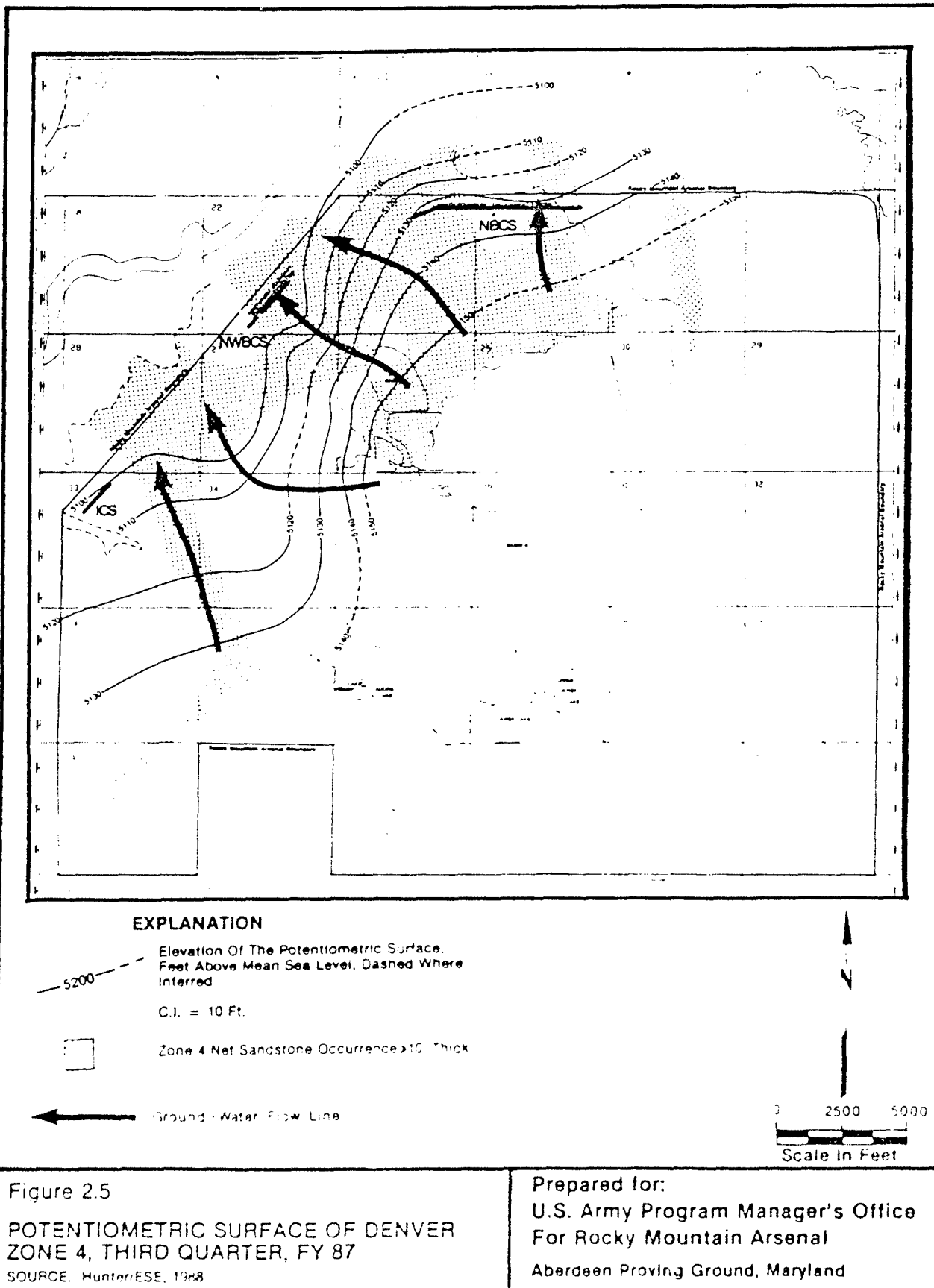
Figure 2.4

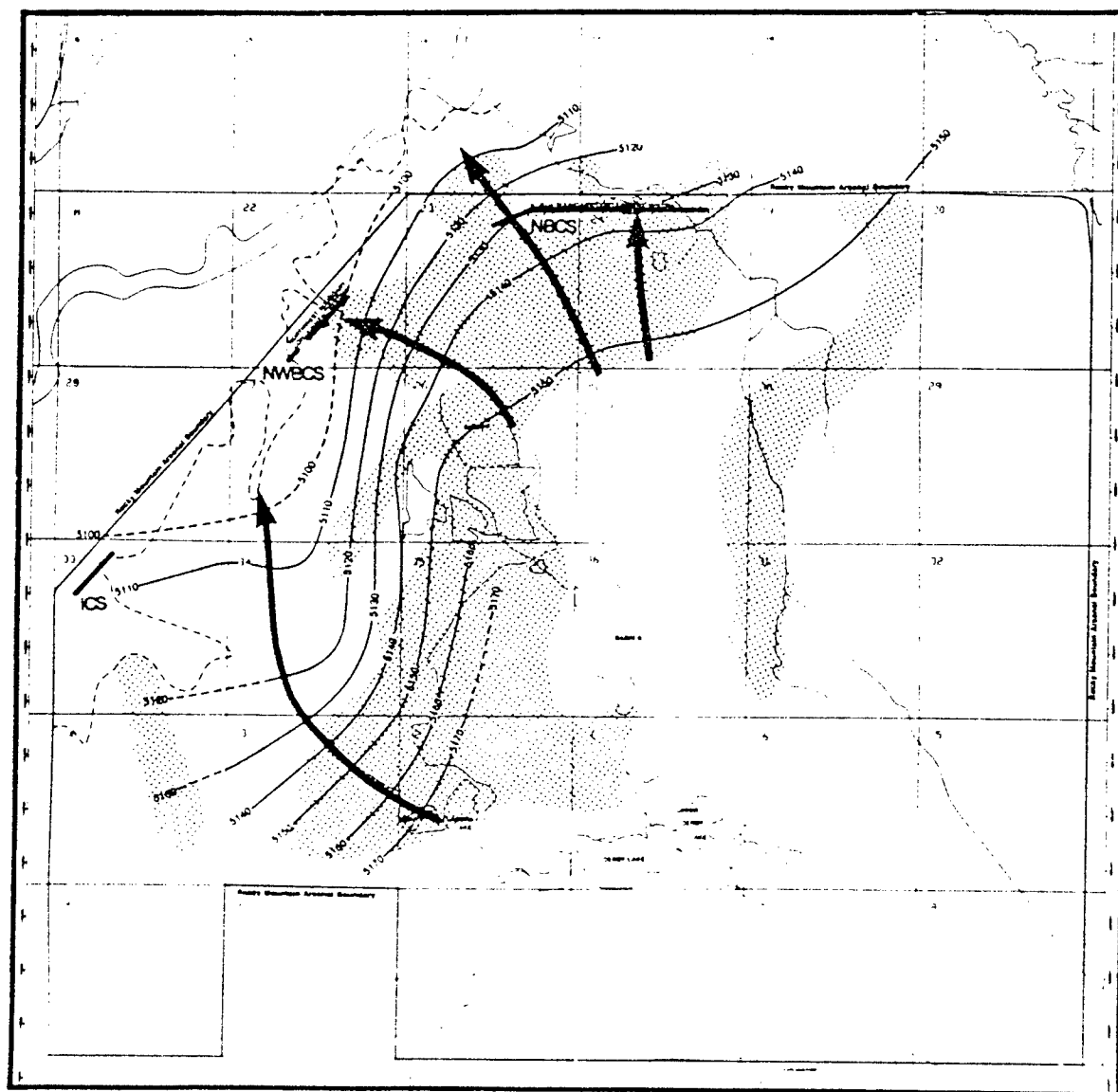
POTENTIOMETRIC SURFACE OF THE UNCONFINED FLOW SYSTEM,
THIRD QUARTER FY 87

SOURCE: MARS 88

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland





EXPLANATION

- Elevation Of The Potentiometric Surface, Feet Above Mean Sea Level, Dashed Where Inferred
 C.I. = 10 Ft.
 Zone 3 Net Sandstone Occurrence >10' Thick
 Ground Water Flow Line

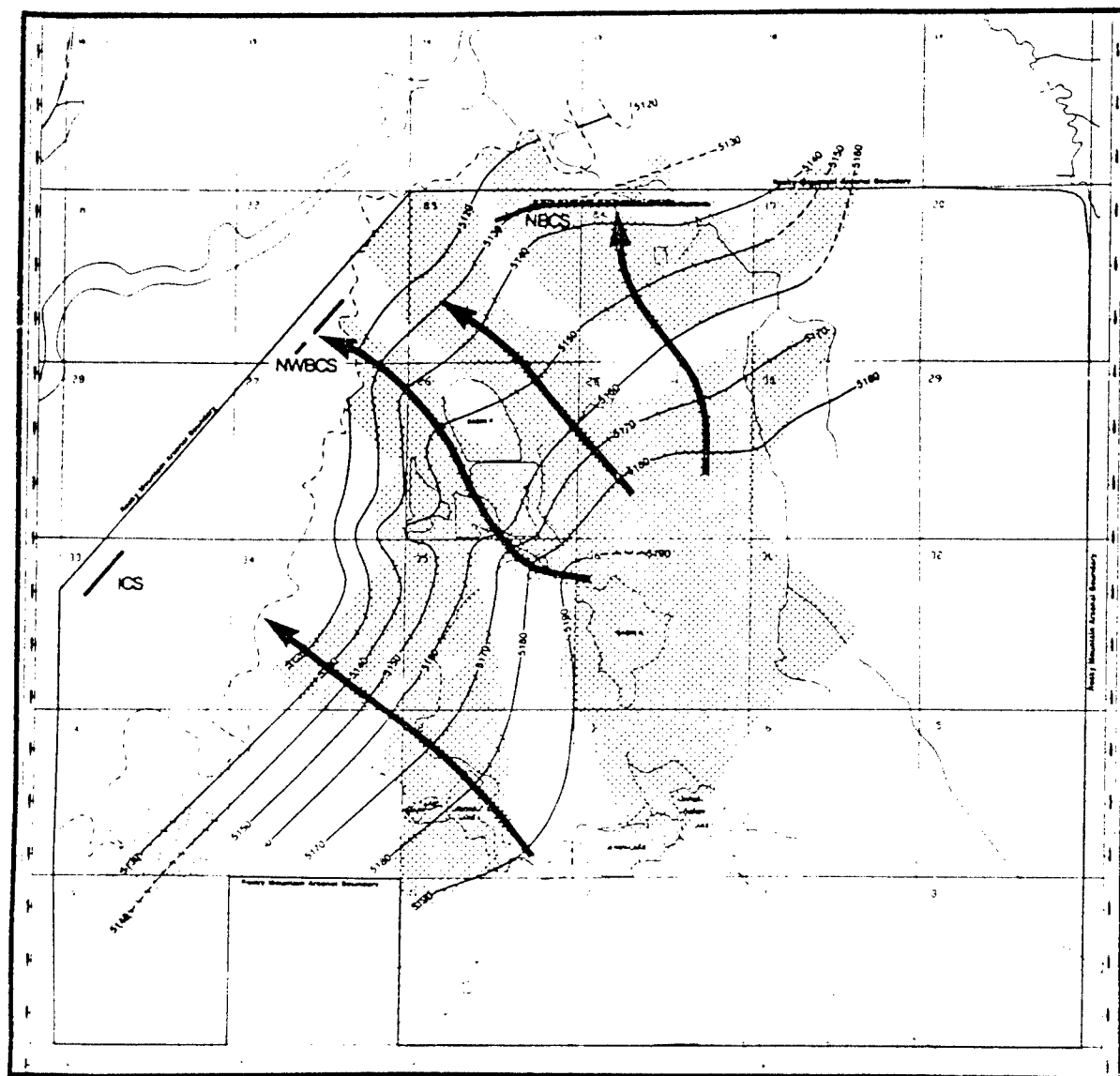
0 2500 5000
Scale In Feet

Figure 2.6

POTENTIOMETRIC SURFACE OF DENVER
ZONE 3, THIRD QUARTER, FY 87

SOURCE Hunter/ESE, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal
Aberdeen Proving Ground, Maryland



EXPLANATION

- 5200 --- Elevation Of The Potentiometric Surface, Feet Above Mean Sea Level, Dashed Where Inferred.
- C.I. = 10 Ft.
- Zone 2 Net Sandstone Occurrence >10' Thick
- Ground Water Flow Line

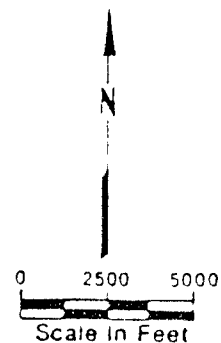
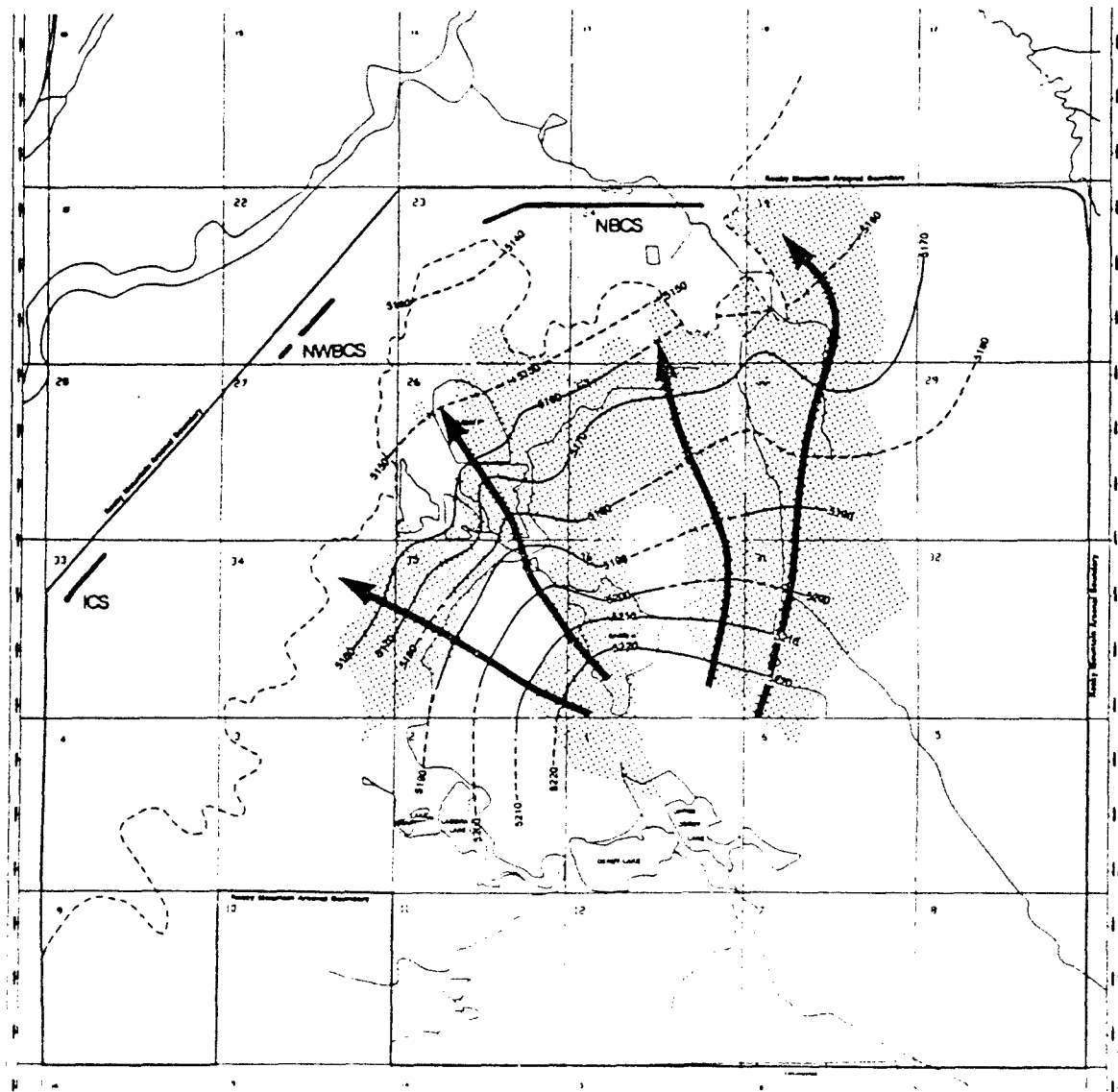


Figure 2.7

POTENTIOMETRIC SURFACE OF DENVER
ZONE 2, THIRD QUARTER, FY 87

SOURCE: Hunter/ISE, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal
Aberdeen Proving Ground, Maryland



EXPLANATION

- 5200 --- Elevation Of The Potentiometric Surface, Feet Above Mean Sea Level, Dashed Where Inferred
- C.I. = 10 Ft.
- Zone 1 Net Sandstone Occurrence >10' Thick
- ← Ground-Water Flow Line

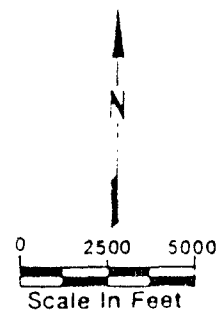
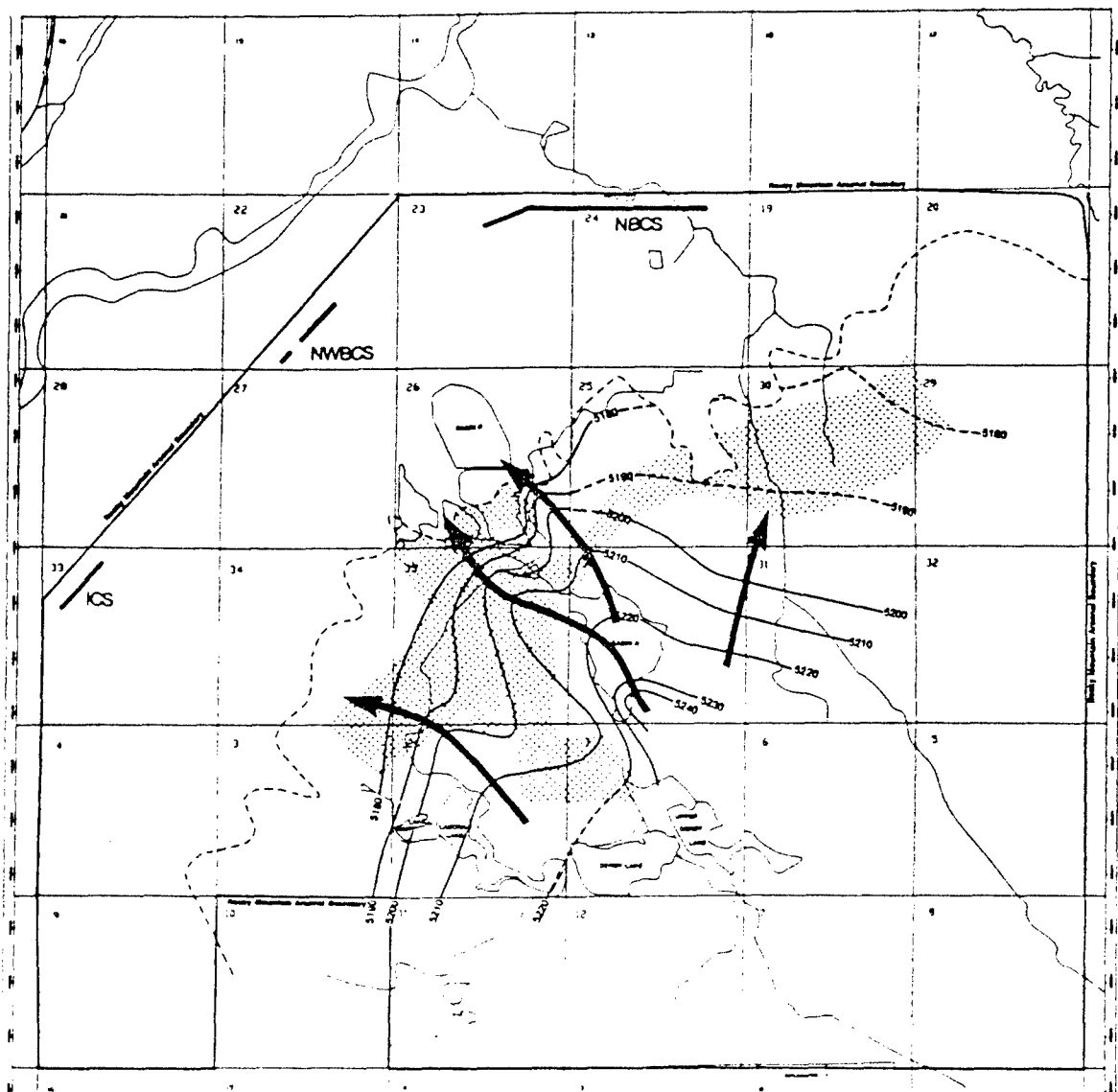


Figure 2.8

POTENTIOMETRIC SURFACE OF DENVER
ONE 1, THIRD QUARTER, FY 87

SOURCE: Hunter/ESE, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal
Aberdeen Proving Ground, Maryland



EXPLANATION

- 5200 --- Elevation Of The Potentiometric Surface,
 Feet Above Mean Sea Level, Dashed Where
 Inferred.
 C.I. = 10 Ft.
 □ Zone 1U Net Sandstone Occurrence >10' Thick
 ← Ground-Water Flow Line

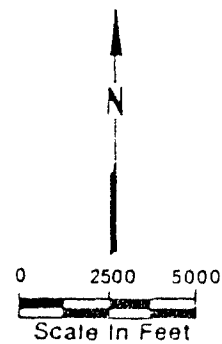
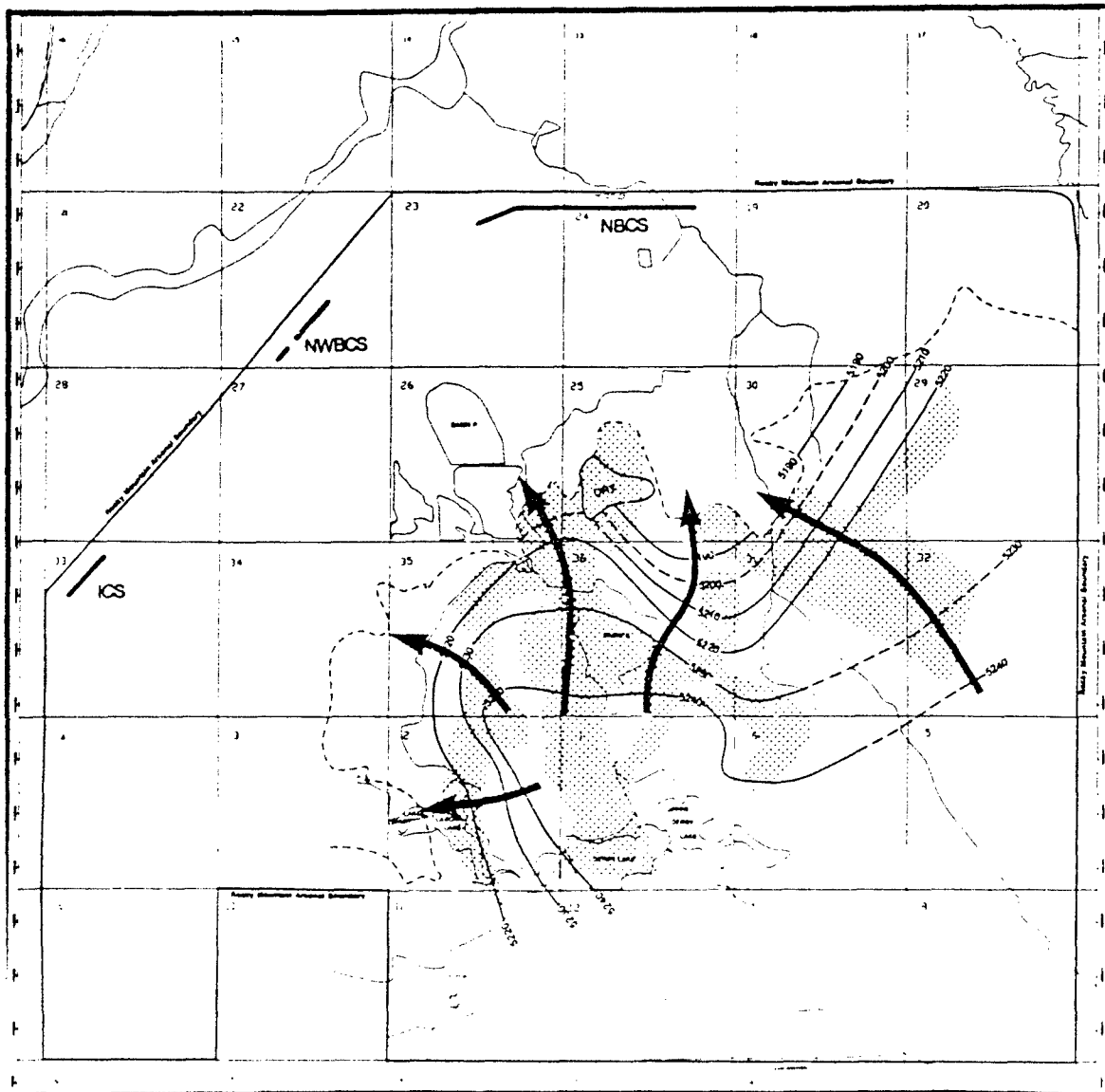


Figure 2.9

POTENTIOMETRIC SURFACE OF DENVER
 ONE 1U, THIRD QUARTER, FY 87

SOURCE: Hunter/ESE, 1988

Prepared for:
 U.S. Army Program Manager's Office
 For Rocky Mountain Arsenal
 Aberdeen Proving Ground, Maryland



EXPLANATION

5200 --- Elevation Of The Potentiometric Surface,
Feet Above Mean Sea Level, Dashed Where
Inferred

C.I. = 10 Ft.



Zone A Net Sandstone Occurrence >10' Thick



Ground-Water Flow Line

0 2500 5000
Scale In Feet

Figure 2.10

POTENTIOMETRIC SURFACE OF DENVER
NE A, THIRD QUARTER, FY 87

IRCE: Hunter/ESE, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal
Aberdeen Proving Ground, Maryland

3.0 NATURE AND EXTENT OF CONTAMINATION

Numerous surface water and groundwater sampling programs have been conducted at RMA to assess the nature and extent of contamination on a regional and site-specific basis. Assessments of contaminant distribution in surface water and groundwater at RMA were achieved by integrating analytical data from recent and historic sampling programs with the hydrogeologic framework established in previous sections of this report. The descriptive assessment of water quality in the Unconfined Flow System and in the Denver aquifer within the Water Remedial Investigation study area is based primarily on the analytical results from the Third Quarter FY87 sampling period. The Third Quarter FY87 sampling program was selected because it contained the greatest number of sample sites and was the most recent comprehensive sampling event. Where necessary, the historic database was used to corroborate or complement Third Quarter data.

Historic programs mentioned here that predate 1985 include the 360° Monitoring Program, the Basin F Monitoring Program, North and Northwest Boundary Containment Systems Monitoring, Irondale Boundary Control System monitoring, and the U.S. Army Corps of Engineer Waterways Experiment Station Regional Monitoring Program. The major groundwater programs undertaken since 1985 include Tasks 4, 25, 36, 38, 39 and 44 (Appendix F, Section 3.0).

Unconfined Flow System and Denver aquifer groundwater contaminant plume maps for the Third Quarter FY87 were constructed using well construction data to differentiate Unconfined Flow System and confined Denver Formation wells. Third Quarter FY87 data were supplemented with historical data from lab records, notebooks, USATHAMA database files, and EPA monitoring programs to help establish plume configurations. Hydrogeologic and geologic information was also used in conjunction with these chemical data to further aid in establishing probable plume configurations. The locations of alluvial and Denver Formation wells included in the Third Quarter FY87 monitoring network are shown on Plates 3 and 4. Wells included in the Third Quarter FY87 sampling network are listed in Table 4.2-1 (Appendix F).

The lowest contour interval value for each plume map represents the highest certified reported limit for that analyte or group of analytes when multiple laboratories analyzed samples during a particular sampling period. If only one laboratory was used to analyze a

particular analyte or group of analytes the CRL for that laboratory is equal to the lowest contour line value on plume maps.

The number and types of contaminants analyzed under various groundwater and surface water sampling programs have evolved over time due to changes in environmental concerns, improved analytical methods, changing RMA activities, and increased knowledge of contaminant fate and migration. The current analytical list was derived from various sources that included:

- o An evaluation of contaminant source characteristics at RMA and compounds attributable to activities at these sites;
- o A review of the historical chemical data and recognition of compounds previously detected; and
- o Additional input from the Parties and State.

Table 3.3-1 (Appendix F) is a comparison of analytical suites from selected historic programs with those of recent Remedial Investigation tasks.

For the purposes of this report, individual analytes have been consolidated into composite groups. Groupings are based primarily on the basis of analytical methodology, although subdivisions within groups reflect similarities in origin, history, and environmental fate. Compounds within a group generally exhibit similar physical and chemical characteristics. As a result, compounds within a group generally display similar behavior with respect to fate and transport in the environment. Brief descriptions of the origin and use of RMA contaminants are presented as part of the discussion of groundwater quality (Section 3.2). Compound characteristics, and mechanisms for migration and attenuation are described in Section 4.4.

Primary and secondary contaminant pathways were identified by contaminant occurrence and plume configuration. These pathways were named to standardize contaminant distribution discussions (Figure 3.1). Names of pathways were determined based on proximity to well known features, and are not meant to imply a source-plume relationship. A complete discussion of pathway identification, including selection criteria, is given in Section 4.5.

Several analytes including chloride, diisopropylmethyl phosphonate, dithiane/oxathiane, aldrin, dieldrin, endrin, dicyclopentadiene, DBCP, chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide and chlorophenylmethyl sulfone are key in assessing the nature and extent of contamination. The relative significance of these contaminants is based on their occurrence, use in RMA industrial or military operations, concentration, and environmental fate and impact.

3.1 Surface Water Quality

The present surface water quality sampling network is essentially an expansion of the 360° Monitoring Program initiated in 1976. Figure 3.2 shows the surface water sampling locations where multiple detections of analytes occurred in samples collected from Fall 1985 through Fall 1987. Analytes detected only once at sites sampled several times during this time period were not included, to place emphasis on those analytes detected multiple times. Detections that occurred at sites sampled only once during this time period were included since data to confirm or deny the occurrences were unavailable. All analyte detections at surface water sampling sites for the periods Fall 1985 through Fall 1987 and Third Quarter FY87 are presented in Tables 4.1-3 and 4.1-2 (Appendix F). A comparison of Tables 4.1-2 and 4.1-3 shows that there is little difference between analyte concentration at given sites through time, although a smaller variety of analytes were detected during the Third Quarter FY87 sampling period than had been detected historically.

Areas where surface water contamination was detected during the Third Quarter FY87 sampling period include South Plants, Basin A, and the Sewage Treatment Plant. Also, surface water samples collected during the Third Quarter FY87 sampling period from water entering RMA from the Peoria Interceptor contained benzothiazole, tetrachloroethylene and 1,1,1-trichloroethane.

3.2 Groundwater Quality

In general, the variety, areal extent and concentrations of contaminants found in the Unconfined Flow System are greater than those found in confined portions of the Denver aquifer. Several compounds or compound groups occur as definable groundwater plumes in the Unconfined Flow System, including volatile halogenated organics, dicyclopentadiene,

volatile aromatic organics, organosulfur compounds, diisopropylmethyl phosphonate, DBCP, organochlorine pesticides, arsenic, fluoride, and chloride. Only a limited number of contaminants occur as definable plumes within the Denver aquifer, including oxathiane/dithiane, chlorobenzene, benzene, dieldrin, fluoride, and chloride. Individual or composite groups of analytes discussed here are included because of their possible toxic effects, historic significance, and relatively widespread distribution in groundwater. Plume maps were constructed for compounds for which there were 10 or more detections for a particular analyte or analyte group. Compounds with too few detections to be presented in plume maps are included in Appendix D as point plot maps.

3.2.1 Volatile Halogenated Organics

The volatile halogenated organics group includes chloroform, trichloroethylene, tetrachloroethylene, methylene chloride, carbon tetrachloride, 1,1-dichloroethylene, trans-1,2-dichloroethylene, 1,1,1-dichloroethane, 1,2-dichloroethane, 1,1,1-trichloroethane, and 1,1,2-trichloroethane. Volatile halogenated organics are commonly used as industrial solvents and degreasers. Although used in the past at RMA, they are also in widespread use elsewhere. Composite concentrations for volatile halogenated organics were calculated by summing the volatile halogenated organic concentrations for each sample, with concentrations below the certified reporting limits set equal to zero. The most frequently detected and widespread volatile halogenated organics at RMA are chloroform, trichloroethylene, and tetrachloroethylene.

Historic water quality data for volatile halogenated organics prior to the Initial Screening Program are very limited, as volatile halogenated organics analysis was not performed regularly until the 1980's. MKE distribution maps for the alluvial and Denver Formation aquifers (MKE, unpublished data, 1986) indicate alluvial occurrences of chloroform and carbon tetrachloride in the South Plants area in Section 1, extending into Sections 2 and 36. In the Denver Formation, chloroform and carbon tetrachloride were detected in the South Plants area; chloroform was also detected in Sections 2, 35 and 36. Initial Screening Program data collected from September 1985 to March 1986 for alluvial wells indicated detections of volatile halogenated organics in several locations, including the Basin A-South Plants area, the Basin F area, the Northwest Boundary Containment System area in Sections 22 and 27, the Central south pathway in Sections 34 and 35, the Western Tier pathway and the Motorpool and Railyard areas of Sections 3, 4, 9 and 33 extending

to the western off-post area. Initial Screening Program data for the Denver Formation for the same time period indicate the volatile halogenated organics occurred mainly as isolated detections in Sections 4, 25, 26, 27, and 35.

A summary of volatile halogenated organic detections from the Third Quarter FY87 sampling period is presented in Appendix F, Table 4.2-5. Concentrations greater than 10,000 ug/l were detected in Sections 23, 26, and 36. The highest concentration, 40,000 ug/l, was detected in the Basin F pathway. Using these data, plumes were delineated (Figure 3.3) in the South Plants-Basin A/Basin A Neck pathways, the Central Pathway, the North Off-post First Creek pathways, the Basin F-Basin F east pathways, Western Tier pathway and the Motor Pool and Railyard pathway.

Isolated occurrences of volatile halogenated organics were detected during the Third Quarter FY87 in the confined Denver Formation (Appendix F, Table 4.2-5). These occurrences are presented in point plot maps in Appendix D (Figures D-99 through D-134). Single compound or composite volatile halogenated organic occurrences were noted in Denver Formation zones A, 1u, 1, 2, 3, 4, 5 and 6. Geographically these detections occurred in Sections 1, 2, 23, 24, 35, 36, and off-post.

3.2.2 Dicyclopentadiene

Dicyclopentadiene is a raw material that was used as a chemical feedstock for production of pesticides in the South Plants complex. Its distribution is associated directly with RMA activities.

Historically dicyclopentadiene has been detected in both alluvial and Denver Formation groundwater at RMA. Historical data collected prior to the Initial Screening Program indicate that dicyclopentadiene occurs from Basin F to the northern RMA border; widespread dicyclopentadiene distribution was detected in Sections 1, 35 and 36, and isolated areas of Sections 18, 22, 27, 33, and 34. These patterns were not confirmed by the Initial Screening Program data. Comparison of the Initial Screening Program alluvial groundwater distribution to the historical data indicated discrepancies in the dicyclopentadiene distributions. Comparison of the Spaine report (1984, RIC#85133R04) data to the Initial Screening Program alluvial data shows wider distribution and

significantly higher concentrations of dicyclopentadiene in groundwater samples analyzed during the 1984 investigation.

A summary of Third Quarter FY87 analytical results for dicyclopentadiene is presented in Table 4.2-17 (Appendix F). The distribution of dicyclopentadiene in the Unconfined Flow System is shown in Figure 3.4. Three plume areas were identified. The largest plume is in the Basin F pathway north from Basin F to the North Boundary Containment System and along the First Creek Off-Post pathway. A second plume extends from northwestern Basin A through the Basin A Neck to the southeastern edge of Basin C. The third plume, extending from South Plants into the middle of Basin A, could not be confirmed by FY87 data due to a lack of sampling in the area. Historical data were reviewed to delineate this plume. The highest concentration of dicyclopentadiene, 1,200 ug/l, was located immediately downgradient of Basin F in Section 23.

Analytical results for dicyclopentadiene samples collected from confined Denver Formation wells during Third Quarter FY87 are presented in Table 4.2-17 (Appendix F, Figures D-140 and D-141). Dicyclopentadiene was not detected in any confined Denver Formation wells.

3.2.3 Volatile Aromatics

The volatile aromatic organics include benzene, chlorobenzene, toluene, ethylbenzene, meta-xylene and ortho- and para-xylenes. They comprise a significant fraction of hydrocarbon fuels, particularly gasoline, and are in common use as industrial solvents. Although used extensively at RMA, they cannot be identified as unique to RMA activities. Composite concentration values reported below were calculated by summing the detected volatile aromatic organics concentrations for each sample. Concentrations below the certified reporting limits were taken to be zero. Volatile aromatic organics are presented as a group in order to provide an overview of their occurrence in RMA groundwater. Chlorobenzene and benzene are the most commonly detected volatile aromatic organic compounds within the Unconfined Flow System and Denver Formation and exert the most influence over the total aromatic plume configurations.

Historical data for volatile aromatic organics prior to 1985 are scarce because earlier analytical programs did not include volatile aromatic organics as target analytes. Data from the Initial Screening Program report (ESE, 1987a, RIC#87253R01) for the period

September 1985 to March 1986 indicated the presence of toluene, benzene, ethylbenzene, and xylene in alluvial groundwater in excess of 1,000 ug/l in the South Plants-Basin A area and north-northeast of Basin F in Section 23. For the same time period, Denver Formation occurrences in excess of 10 ug/l were noted in Sections 1, 22, 23, 26 and 35 with isolated, relatively low-level detections in Sections 2, 3, 4, 6, 19, 25 and 32.

A summary of Third Quarter FY87 analytical results is presented in Table 4.2-5 (Appendix F). Volatile aromatic organics were detected in the Unconfined Flow System in the South Plants-Basin A area northward to the Basin A Neck pathway, in the Basin F pathway, and off-post in the Northern, First Creek, and Quincy Street pathways. The distribution of summed volatile aromatic compounds is shown in Figure 3.5. The highest detected concentration of volatile aromatic organics was 56,000 ug/l in the southwestern portion of Section 36. Elevated concentrations of benzene and other volatile aromatic compounds have been detected during a recent sampling event conducted in the South Plants area by MKE. The results of this sampling event are presented in the South Plants Study Area Report.

The volatile aromatic compounds occur more extensively in the confined Denver Formation than any other organic compound groups identified at RMA. Volatile aromatic organics were detected in confined Denver Formation zones A, 1u, 1, 2, 3, 4 and 5. Geographically these detections occurred in Sections 1, 23, 24, 26, 35, 36, and off-post in Sections 13 and 14, downgradient of the North Boundary Containment System (Appendix D, Figures D-75 through D-98).

3.2.4 Organosulfur Compounds

Organosulfur compounds detected at RMA include chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, chlorophenylmethyl sulfone, dithiane, oxathiane, and benzothiazole. The organosulfur compounds chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, and chlorophenylmethyl sulfone are presented as a composite group because the individual compounds have similar chemical and physical properties, and are derived from the manufacture of Planavin in the South Plants complex, and have similar distributions and concentrations. Dithiane and oxathiane have distributions similar to those of chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, and chlorophenylmethyl sulfone, but result from degradation of mustard agent and will be discussed separately.

Mustard was manufactured, handled, and demilitarized in the North and South Plants complexes. Benzothiazole is a relatively recent addition to the RMA analyte list and will be discussed separately.

Historically, chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, and chlorophenylmethyl sulfone have been detected in both the Unconfined Flow System and Denver Formation aquifers. The distributions of these compounds identified during the Initial Screening Program confirmed general historical distributions identified prior to the Initial Screening Program. In general, the distribution of chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, and chlorophenylmethyl sulfone detected in the Unconfined Flow System during the Initial Screening Program indicated an association with several recognized source areas at RMA, including the South Plants area, Basin A, and Basin F. Total concentrations ranged from 10 to 100 ug/l or greater. These compounds were also detected in the Unconfined Flow System along the north boundary of RMA (Sec. 23 and 24) in concentrations in excess of 10 ug/l.

The distribution of chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, and chlorophenylmethyl sulfone in the confined Denver Formation was largely restricted to the vicinity of Basins B, C, and D in Section 26, and the northern portion of Section 35. Total concentrations generally ranged from 1.3 to 10 ug/l in this area.

During the Initial Screening Program dithiane and oxathiane were detected in both alluvial and Denver Formation groundwater at RMA. Distributions in the alluvial aquifer were in the vicinity of Basins A through F, and north from Basin F to the north boundary of RMA. Also during the Initial Screening Program, dithiane and oxathiane were detected in confined Denver Formation groundwater in the vicinity of Basins B, C, and D in Section 26, and in the northern portion of Section 35. Analytical data from 1974 through 1985 indicate the presence of these compounds in Basins C, D, and E, north-northeast of Basin F, and in isolated areas of Section 36.

Benzothiazole is a heterocyclic aromatic compound associated with the manufacture of pesticides. Historically, analyses for benzothiazole were not routinely performed on RMA groundwater samples. Benzothiazole analyses were reported on an occasional basis between 1975 and 1984. Based on the results of analyses, benzothiazole was recognized as a

possible constituent in RMA groundwater and was added to the RMA target analyte list during Second Quarter FY87.

A summary of Third Quarter FY87 composite analytical results for chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, and chlorophenylmethyl sulfone is presented in Appendix F, Table 4.2-10. Two plumes were identified in the Unconfined Flow System (Figure 3.6), in the areas of the Basin F pathway and the South Plants-Basin A/Basin A Neck pathways. Total concentrations of chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, and chlorophenylmethyl sulfone within these plumes range from 6.2 to 2,100 ug/l on-post and 5.2 to 160 ug/l off-post. The highest on-post concentration was noted approximately 600 ft northeast of Basin F. The highest off-post concentration was noted approximately 2,500 ft north of the RMA boundary in west-central Section 13.

A summary of Third Quarter FY87 analytical results for dithiane and oxathiane is presented in Appendix F, Table 4.2-8. The areal distribution of these compounds is shown on the plume map presented in Appendix F, Figure 4.2-5. Dithiane and oxathiane distribution in the Unconfined Flow System is very similar to the distribution of chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, and chlorophenylmethyl sulfone, occurring in an apparently continuous plume along the South Plants/Basin A pathway, through the Basin F east and Basin F pathways, and north to the North Boundary Containment System. The plume extends off-post along the First Creek pathway. Greatest concentrations of dithiane and oxathiane occur in the South Plants/Basin A area, ranging from 57 to 9,300 ug/l.

The distribution of benzothiazole in the Unconfined Flow System based on Third Quarter FY87 analyses (Appendix F, Table 4.2-9) is shown on the plume map in Appendix F, Figure 4.2-7. Plumes were identified in the Basin F pathway and in the Basin A pathway. The highest concentration, 15 ug/l, was detected in the Basin A pathway.

Chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, and chlorophenylmethyl sulfone were detected in Third Quarter FY87 samples collected from confined Denver Formation wells completed within zones A, 1u, 1 and 2 (Appendix F, Table 4.2-10). The distribution of chlorophenylmethyl sulfide, chlorophenylmethyl sulfoxide, and chlorophenylmethyl sulfone in confined Denver Formation groundwater was primarily confined to the vicinity of Basins B, C, and D in Section 26 and the northern portion of Section 35 (Appendix D,

Figures D-63 through D-74). The highest concentrations were observed in isolated wells in Section 2 (48 ug/l) and Section 26 (64 ug/l).

Dithiane/oxathiane were observed in samples collected from confined Denver Formation wells completed within zones 1u, 1, 2 and 4 (Appendix F, Table 4.2-8). These detections are located in the vicinity of Basin C, Basin A Neck pathway, and the Basin F North pathway. The locations of wells completed within these zones and detected dithiane/oxathiane concentrations are shown on the point plot maps in Appendix D (Figures D-40 through D-55). The highest concentration detected was 310 ug/l, in the vicinity of Basin C.

Benzothiazole was detected in confined Denver Formation wells completed within zones 1U, 1, 4, and 5 (Appendix F, Table 4.2-9). The locations of wells completed within each of these zones and detected benzothiazole concentrations are shown on point plot maps in Appendix D (Figures D-56 through D-62). Benzothiazole was detected in the Basin A Neck area near the eastern margin of Basin C and in isolated wells in Sections 3 and 4. The highest concentration, 3.4 ug/l, was detected in the Basin A Neck area.

3.2.5 Diisopropylmethyl Phosphonate

Diisopropylmethyl phosphonate is a byproduct of the manufacture of the nerve agent GB (Sarin) in the North Plants complex. This compound is directly associated with RMA activities.

Historically, diisopropylmethyl phosphonate has been detected in both alluvial and confined Denver Formation groundwater at RMA. During the Initial Screening Program, diisopropylmethyl phosphonate was detected in the alluvial aquifer from the Basin A/Basin A neck pathway to Basins B through F, to the north and northwestern RMA boundaries in Sections 23 and 24. Diisopropylmethyl phosphonate was detected in confined Denver Formation wells in an area extending from the Basin A Neck through Basin B to the northern portion of Basin C.

A summary of analytical results for diisopropylmethyl phosphonate analyses in the Unconfined Flow System during Third Quarter FY87 is presented in Table 4.2-18 (Appendix F). The distribution of diisopropylmethyl phosphonate in the Unconfined Flow System is

shown in Figure 3.7. The diisopropylmethyl phosphonate plume occurs in an area extending from Basin A through Basin A Neck, northward through the Basin F pathway to the north RMA boundary, continuing off-post along the First Creek and the Northern off-post pathways to near the South Platte River. The highest concentration detected was 5,200 ug/l, in Section 26.

A summary of analytical results for diisopropylmethyl phosphonate in groundwater samples from confined Denver Formation wells for third Quarter FY87 is presented in Appendix F, Table 4.2-18. Diisopropylmethyl phosphonate was detected in samples collected from confined Denver Formation wells completed in zones A, 1u, 1, 2, 3 and 5. The locations of wells completed in each of these zones and detected diisopropylmethyl phosphonate concentrations are shown on point plot maps in Appendix D (Figures D-142 through D-148). The highest concentration detected was 5,400 ug/l, in a well completed in zone 1u in Section 35.

3.2.6 DBCP

DBCP is a nematocide and soil fumigant. It was manufactured by Shell in the South Plants complex and shipped in tank cars which were stored in the Rail Classification Yard.

Historically, DBCP has been detected in both the Unconfined Flow System and confined Denver Formation groundwater systems at RMA. According to Initial Screening Program data, the highest concentrations of DBCP in the Unconfined Flow System were observed in the South Plants area, the southern portion of Basin A, an area extending from southeastern Section 4 to the Irondale Boundary Control System, and an area north of Basin F in Sections 23 and 26. Within the confined Denver Formation DBCP was detected only twice, in Sections 2 and 6. DBCP was detected between 1979 and 1983 in samples from the alluvial aquifer in the South Plants-Basin A area through Basins A, B, C, D, E, and F to the Northwest Containment System and North Boundary Containment System. Analyses performed on Denver Formation samples between 1978 and 1983 detected DBCP in Sections 26 and 35 near Basins B, C, and D (MKE, unpublished data, 1986).

A summary of Third Quarter FY87 analytical results for DBCP is presented in Appendix F, Table 4.2-16. Plume configurations for DBCP in the Unconfined Flow System are shown in Figure 3.8. Plumes were identified in the Basin F pathway from Basin F to the northern

RMA boundary, in the Northern Off-Post pathway in Section 11, in the Basin A pathway and along the Basin A Neck pathway through Sections 26 and 27 to an area near the Northwest Containment System, and in the Motor Pool and Railyard pathway extending northward to the Irondale Boundary Control System.

A summary of analytical results for confined Denver Formation wells analyzed for DBCP during Third Quarter FY87 is presented in Appendix F, Table 4.2-16. DBCP was detected in confined Denver Formation wells completed in zones A, 2, and 4. The locations of wells completed within each of these zones and detected DBCP concentrations are shown on point plot maps presented in Appendix D (Figures D-135 through D-139). DBCP was detected in confined Denver Formation wells in Sections 1 and 23, and off-post immediately downgradient of the North Boundary Containment System. The highest concentration detected, 0.78 ug/l, was noted in confined Denver Formation zone 2.

3.2.7 Organochlorine Pesticides

Organochlorine pesticides were manufactured at RMA by CF&I, Julius Hyman and Company, and Shell in the South Plants complex. Organochlorine pesticides have been used in farming land adjacent to RMA.

The distribution of organochlorine pesticide is largely the result of dieldrin and endrin occurrences and to a much lesser extent of aldrin and isodrin. For this reason, plume maps were generated only for dieldrin and endrin, which will be discussed below.

Historically organochlorine pesticides have been detected in alluvial and Denver Formation aquifers. Based on Initial Screening Program data, concentrations in excess of 1.00 ug/l were observed locally in alluvial groundwater in Sections 1, 2, 23, 24, 26, 35 and 36. Isolated detections of organochlorine pesticides in Denver Formation groundwater were observed in Sections 2, 4, 19, 25, 26 and 36.

Summaries of Third Quarter FY87 analytical results for dieldrin and endrin are presented in Tables 4.2-6 and 4.2-7 (Appendix F). The distribution of dieldrin and endrin in the Unconfined Flow System is shown on plume maps presented in Figure 3.9 and Appendix F, Figure 4.2-4, respectively. Six major plumes were identified in the following pathways: Central pathway south, Central pathway north, South Plants/Basin A, Basin A Neck

pathways to Section 27, Basin F pathway, and Basin F northwest pathway. Within downgradient off-post areas dieldrin was detected north and northwest of the RMA boundary; endrin was detected only north of the RMA boundary. Contaminant trends in and around the North Boundary Containment System and Northwest Boundary Containment System are discussed further in Task 36 (ESE, 1988e, RIC#88344R02), Task 25 (ESE, 1988f, RIC#89024R02) and Task 39 (ESE, 1989b, RIC#89024R01).

Based on Third Quarter FY87 analytical results, dieldrin and/or endrin were detected in confined Denver Formation wells completed in zones A, 1, 2 and 3 (Appendix F, Tables 4.2-6 and 4.2-7). The locations of wells completed within each of these zones and detected concentrations are shown on the point plot maps in Appendix D (Figures D-28 through D-34).

3.2.8 Arsenic

Arsenic is a naturally occurring element. It was also a component of Lewisite as well as a byproduct of Lewisite manufacture (Ebasco, 1988b, RIC#88357R01). Historically arsenic has been detected in groundwater samples in Sections 1, 2, 4, 19, 23, 24, 26, 27, 32, 35, and 36. Although arsenic may be found naturally, there has been no value recognized by RMA investigators or regulators as representative of background levels of arsenic in groundwater at RMA. Therefore, a plume is defined here by concentrations of arsenic in excess of 3.07 ug/l, which is the highest certified reporting limit for Third Quarter FY87 data for arsenic.

In considering background levels of arsenic in RMA groundwater, it is worthy of note that arsenic detections, even very close to the CRL, were largely limited to known RMA source areas. This indicates that background levels of arsenic are probably very low in the RMA area.

A summary of Third Quarter FY87 analytical results for total arsenic in alluvial and Denver Formation wells completed within the Unconfined Flow System is presented in Appendix F, Table 4.2-19. Arsenic plumes were delineated in the Basin A/Basin A Neck pathway and the Basin F pathway, with minor occurrences in the First Creek off-post pathway and the Quincy Street pathway (Appendix F, Figure 4.2-21). The highest concentration detected was 410 ug/l, in the Basin F pathway plume.

Arsenic was detected within wells screened in the confined Denver Formation during the Third Quarter FY87 sampling period. A summary of analytical results for these samples is presented in Appendix F, Table 4.2-19. Arsenic was detected in samples from wells screened in confined Denver Formation zones A, 1u, 1, 2, 4, and 5, (Appendix D, Figures D-162 through D168). These detections occurred in Sections 3, 4, 6, 8, 22, 24, 26, 35, and 36. The highest detected concentration was 27 ug/l, in zone A in section 36.

3.2.9 Fluoride

Fluoride is a naturally occurring anion. It was used at RMA in the elemental form of fluorine in the manufacture of nerve gas (Ebasco, 1988b, RIC#88357R01). During the Initial Screening Program, fluoride in the alluvial groundwater system was detected at concentrations up to 310,000 ug/l. Concentrations above 5,000 ug/l were observed in the area of Basin A, north of Basin F, and in the vicinity of the North Boundary Containment System. Within the Denver Formation, fluoride was observed during the Initial Screening Program at concentrations in excess of 1,200 ug/l over an area encompassing most of the western two-thirds of RMA. The distribution of fluoride within the deeper Denver Formation, in wells with screen tops greater than 50 ft below the bedrock contact, was less widespread than the overall Denver distribution. A comparison of Initial Screening Program data for fluoride analyses to the historical USATHAMA database and data obtained from the Spaine report (1984, RIC#85133R04) confirms general distribution trends of fluoride in the alluvial aquifer, principally associated with the primary source areas.

A summary of Third Quarter FY87 analytical results for fluoride (as a dissolved anion) in alluvial and Denver Formation wells completed within the Unconfined Flow System is presented in Appendix F, Table 4.2-20. The distribution of fluoride in the Unconfined Flow System is shown in Appendix F, Figure 4.2-22. Background levels for fluoride have not been defined for the RMA area; however, values for fluoride in upgradient wells shown in Table 3.1 range from 570 to 1,000 ug/l. For the purposes of this report, based largely upon the highest CRL value for fluoride in FY88 monitoring, fluoride plumes have been defined here as those areas where concentrations are in excess of 1,220 ug/l. Three plumes were identified; the largest extends from the South Plants/Lower Lakes area through Basins A through F to beyond the RMA north and northwestern boundaries; a

Table 3.1 Representative Concentrations for Naturally Occurring Constituents in RMA Upgradient Unconfined Wells
(Values are in ug/l)

Analyte	Unconfined Well (approximately 0.5 miles south east of RMA) ¹	Well Number ²		Concentration Range From Upgradient Wells
		12001	11001	
Chloride	*	34,000	52,000	34,000-60,000
Fluoride	1,000	690	570	570-1,000
Sulfate	48,000	63,000	132,000	43,000-138,000
Calcium	51,000	67,000	139,000	51,000-139,000
Potassium	*	*	*	NA
Sodium	36,000	44,000	62,000	36,000-68,000
Magnesium	9,200	*	*	9,200
Nitrogen	8,300	3,500	700	700-22,900
Zinc	*	*	*	NA
Cadmium	*	*	*	NA
Lead	*	*	*	NA
Chromium	*	*	*	NA
Copper	*	*	*	NA
Arsenic	*	*	*	NA
Mercury	*	*	*	NA
pH	*	*	*	NA
Conductivity	*	*	*	7.5 875

1 Irrigation well, 70 ft deep, in Section 17, T3S, R66W (McConaghy et al., 1964).

2 Alluvial wells near southern boundary of RMA, samples collected 1975 and 1976 (Army, RIC#82160R12).
* Not analyzed.

Source: HLA, 1988.

second plume extends from west-central Section 35 to the northwest corner of Section 34, and a third plume extends a short distance within Section 2. The highest concentration detected during Third Quarter FY87, 220,000 ug/l, was adjacent to the north side of Basin F.

Based on Third Quarter FY87 analytical results, fluoride was detected in samples collected from confined Denver Formation wells completed within every zone except the VC/VC₂ zone (Appendix F, Table 4.2-20). Plumes were constructed based on fluoride concentrations within Denver Formation zones A, 1u, 1, 2, 4, and 5 (Appendix F, Figures 4.2-23 through 4.2-28). Concentration point plot maps were generated for the remaining Denver Formation zones and are in Appendix D (Figures D-157 through D-161). Fluoride plumes were delineated in Sections 1, 2, 3, 4, 22, 23, 25, 26, 35, and 36. The highest concentration detected was 7,900 ug/l, in north-central Section 4.

3.2.10 Chloride

Chloride is a naturally occurring anion which is also prevalent in salts and solvents associated with several processes that were conducted at RMA (Ebasco, 1988b, RIC#88357R01). Historically, widespread occurrences of chloride have been detected in both the Unconfined Flow System and confined Denver Formation at RMA. The distribution of chloride detected in the Unconfined Flow System in concentrations greater than 250,000 ug/l during the Initial Screening Program extends from the South Plants area to the northern and northwestern RMA boundaries. Initial Screening Program data also indicate that chloride was detected in the Denver aquifer at concentrations in excess of 250,000 ug/l in three areas; the South Plants area, Basins C through F, and Sections 22 and 23 near the northern RMA boundary.

Historical groundwater data collected prior to the Initial Screening Program show more widespread chloride distributions in both the Unconfined Flow System and confined Denver Formation than Initial Screening Program data indicate. Based on historical data chloride extends further east, west, and south than chloride distributions indicated by Initial Screening Program data. Within the Denver Formation, historical data imply a continuous distribution of elevated chloride concentrations extending from the South Plants area to the northwestern RMA boundary.

A summary of Third Quarter FY87 analytical results for chloride in the Unconfined Flow System is presented in Appendix F, Table 4.2-21. Table 3.1 lists values for inorganic parameters for several unconfined upgradient wells. For the purpose of this report, this well was used to represent typical background chloride concentrations. The upgradient chloride range is from 34,000 to 60,000 ug/l. Drinking water standards established by the EPA indicate that 250,000 ug/l is the maximum allowable concentration. In light of this, 150,000 ug/l was used as the lowest contour interval, to be sure that all potentially anomalous occurrences were considered in plume mapping. The distribution of chloride in the Unconfined Flow System is shown in Appendix F, Figure 4.2-29. Third Quarter FY87 data for chloride compare more closely with Initial Screening Program data than with historical data. Chloride concentrations in the Unconfined Flow System ranged from 5,700 to 28,000,000 ug/l. Concentrations in excess of 1,000,000 ug/l were observed along the Basin A/Basin A Neck pathway, through Basins B, C, D, and F, and along the Basin F pathway north to the North Boundary Containment System. The highest chloride concentration in Unconfined Flow System wells analyzed was located in Section 26, just northeast of Basin F.

A summary of chloride analyses from groundwater samples collected from confined Denver Formation wells during the Third Quarter FY87 sampling program is presented in Appendix F, Table 4.2-21. Chloride was detected in samples collected from confined Denver Formation wells completed in every zone except the VC/VCE. Plume maps were constructed based on chloride concentrations within zones A, 1, 2, 3, and 4 and are presented in Appendix F (Figures 4.2-30 through 4.2-34). The locations of wells and detected chloride concentrations in the remaining confined Denver Formation zones are shown on point plot maps in Appendix D (Figures D-151 through D-156). The greatest chloride concentration detected in the confined Denver Formation was 7,300,000 ug/l, in zone A in northern Section 2.

3.2.11 GC/MS Analysis

Gas chromatograph/mass spectrometry (GC/MS) were conducted on samples analyzed under Task 4 (3rd and 4th Quarters FY86) and Task 44 (3rd Quarter FY87) to confirm identification of target analytes using other analytical techniques and to tentatively identify nontarget compounds.

A detailed discussion of GC/MS analytical methods, criteria for well selection for GC/MS analysis, QA/QC procedures, and target and nontarget analytical results can be found in Appendix F, Section 4.3. In addition, all analytical data for groundwater analyses performed by GC/MS are contained in Appendix D.

3.2.12 Vertical Extent of Contamination

The purpose of this section is to describe depths of groundwater contaminants that have been detected at RMA. The mechanisms by which contaminants migrated in the Unconfined Flow System and eventually to deeper zones (approximately 200 ft) of the Denver Formation are discussed in Section 4.0. Data used to assess the depth of groundwater contamination in the Denver Formation were generated from the Initial Screening Program through the Summer 1987 sampling periods. Data from several sampling periods were used in order that the reproducibility and associated reliability of the data could be assessed. To aid in this assessment, composite maps were generated which delineate the extent of organic and inorganic analytes from Denver Formation zones A, B, and 1 through 7 (Figure 3.10-3.27).

The composite organic plume maps (Figures 3.20-3.27) show that most organic analytes detected in deeper zones of the Denver Formation (zones 2-7) are located in the area between Basin F and off-post Sections 13 and 14, which are adjacent to and north of the north boundary containment system. Organic analytes have been detected in this area at depths of approximately 160 ft below ground surface. Near the southeast corner of Basin F, dieldrin and endrin have been detected at concentrations of 1.2 ug/l and 0.16 ug/l at a depth of 146 ft. In the vicinity of the north boundary, chloroform at 3.1 ug/l, chlorobenzene at 7.74 ug/l, and diisopropylmethyl phosphonate at 27 ug/l have been detected from depths of approximately 150 to 180 ft.

Chloroform has been detected in the deepest screened well in the South Plants at a depth of 210 ft below ground surface. Detected concentrations of chloroform exceed 100 ug/l in the Unconfined Flow System at South Plants but are less than 10 ug/l in the deepest well. Several wells were installed during Autumn 1988 in the South Plants to further assess the extent of vertical contamination in the South Plants area. Results of water samples obtained from these wells will be included in the FY89 annual report of the Comprehensive Monitoring Program.

North of the South Plants in the Basin A/Basin A Neck areas, organic analytes have been detected at depths of approximately 100 ft below ground surface. These analytes include oxathiane, dithiane, benzothiazole, chlorophenylmethyl sulfide, chlorobenzene, trichloroethylene and benzene. All of these analytes were detected at lower concentrations at depth than in the overlying Unconfined Flow System. For example, oxathiane was detected at a concentration of approximately 50 ug/l in the Unconfined flow System and at 17 ug/l in Denver Formation zone 1U. Organic analytes have also been detected in deeper zones of the Denver Formation in what appear to be isolated occurrences in Sections 3, 4, and 9 at depths of 150 to 200 ft, Section 27 at depths of 100 to 150 ft, and Section 33 at depths of 50 to 100 ft below ground surface. The deepest wells in these sections should be resampled to confirm prior analyses.

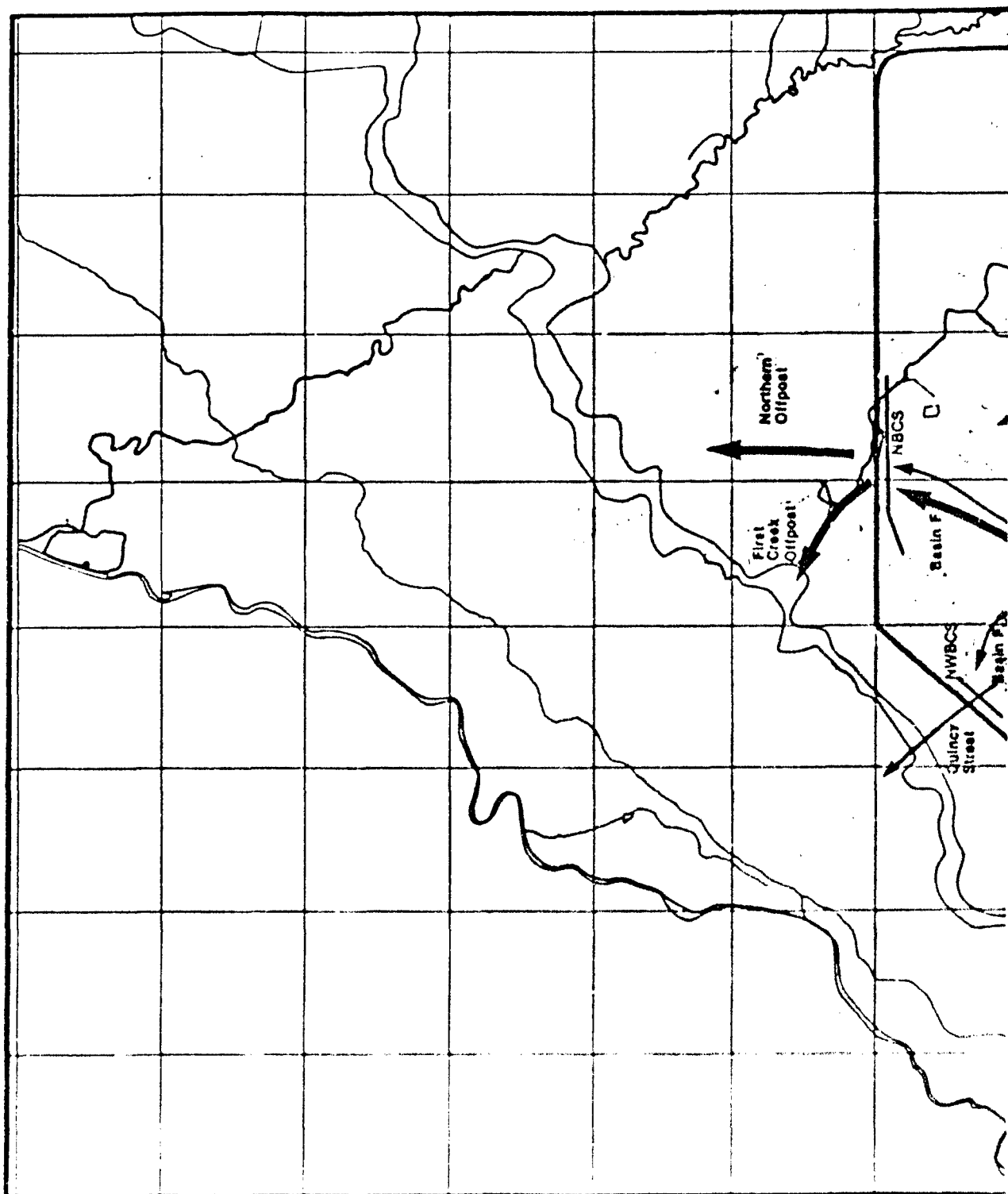
Concentrations of fluoride, chloride, and arsenic above background levels have been detected in deeper zones of the Denver Formation both north and northwest of Basin F (Figures 3.16 - 3.18). These inorganic analytes have been detected along the northern and northwestern portion of RMA at depths of approximately 160 ft below ground surface. As with organic analytes, the concentration of inorganic analytes decreases with depth. For example, concentrations of chloride in the Unconfined Flow System north and northwest of Basin F range from 150,000 to over 1,000,000 ug/l. Concentrations of chloride in the deeper zones of the Denver Formation (zones 6 and 7) are less than 15,000 ug/l. Similarly, fluoride concentrations in the Unconfined Flow System range from 1,220 to over 10,000 ug/l, but are less than 2,500 ug/l in the deeper Denver Formation zones.

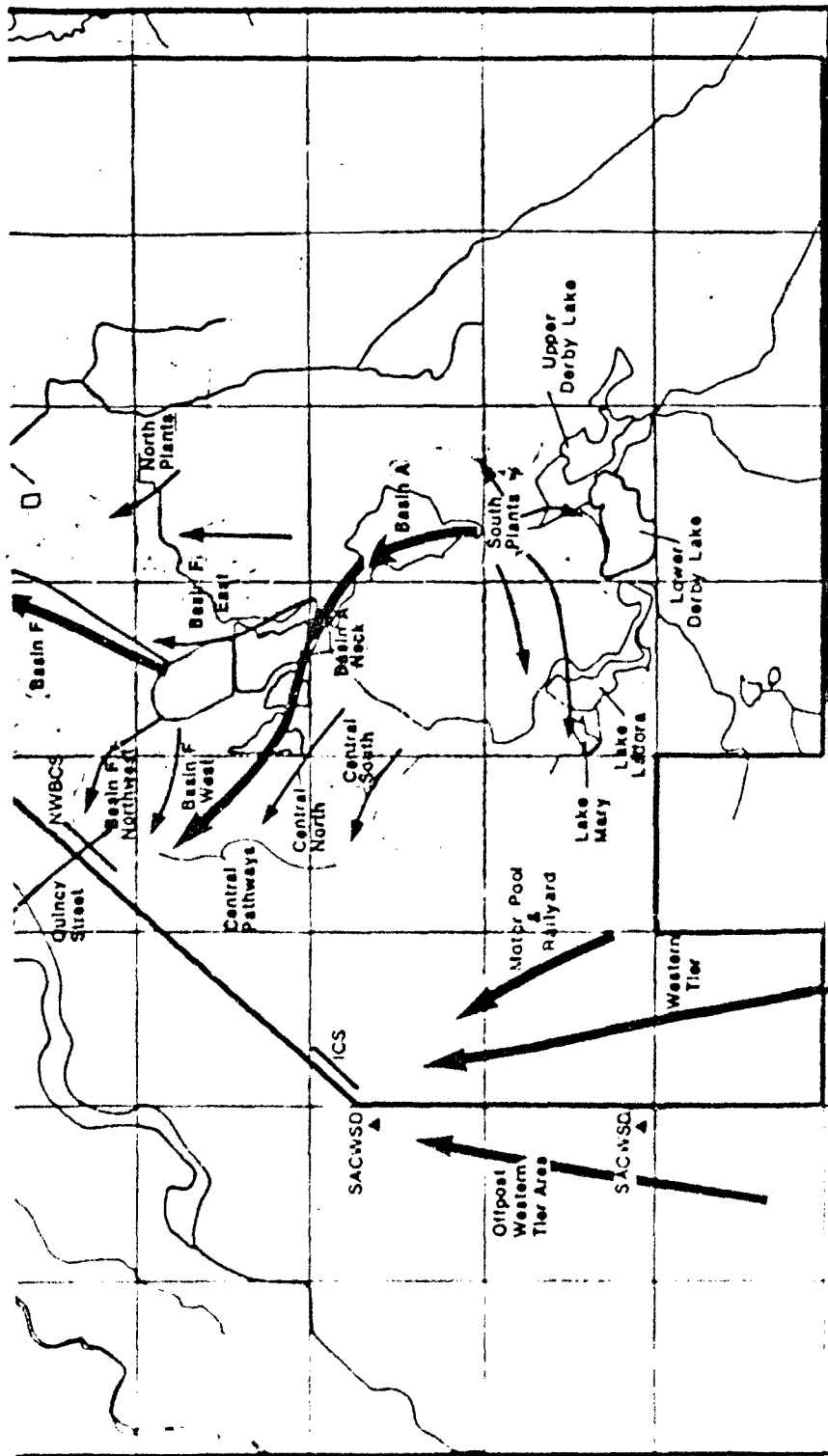
Most detections of inorganic analytes from deeper zones of the Denver Formation beneath South Plants occur at depths of 145 ft or less. However, inorganic analytes have been detected above background levels (chloride at 62,600 ug/l; fluoride at 1,720 ug/l) in the deepest well (Well 01048) at South Plants at a depth of 210 ft. Concentrations of chloride in the Unconfined Flow System in South Plants range from 150,000 to over 500,000 ug/l and range from approximately 28,000 to 88,000 ug/l at depths of 145 ft.

Inorganic analytes have been detected above background levels in the Basin A/Basin A Neck area at depths of approximately 145 ft. Concentrations of chloride above 1,000,000 ug/l are common in the Unconfined Flow System in this area, but are generally less than 250,000 ug/l in deeper zones of the Denver Formation. Fluoride concentrations generally

range from 2,000 to 5,000 ug/l in the Unconfined Flow System in this area and generally are less than 2,000 ug/l in deeper Denver Formation zones.

Inorganic analytes have also been detected above background levels in isolated locations within Sections 3, 4, 8, 9, 25, 32, 33, and 34.





EXPLANATION

- Primary Pathway
- Secondary Pathway
- Unsatuated Alluvium
- ICS Ironstone Containment System
- NWBCS Northwest Boundary Containment System
- NBCS North Boundary Containment System
- SACWSD South Adams County Water Supply District Well

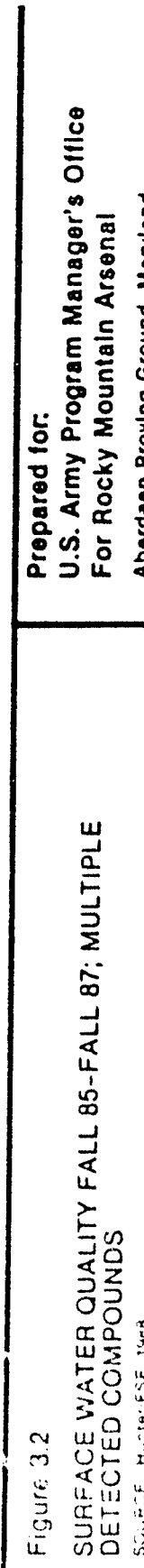
Figure 3.1

RMA CONTAMINANT MIGRATION PATHWAYS

SOURCE: HUNT, 1995

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland

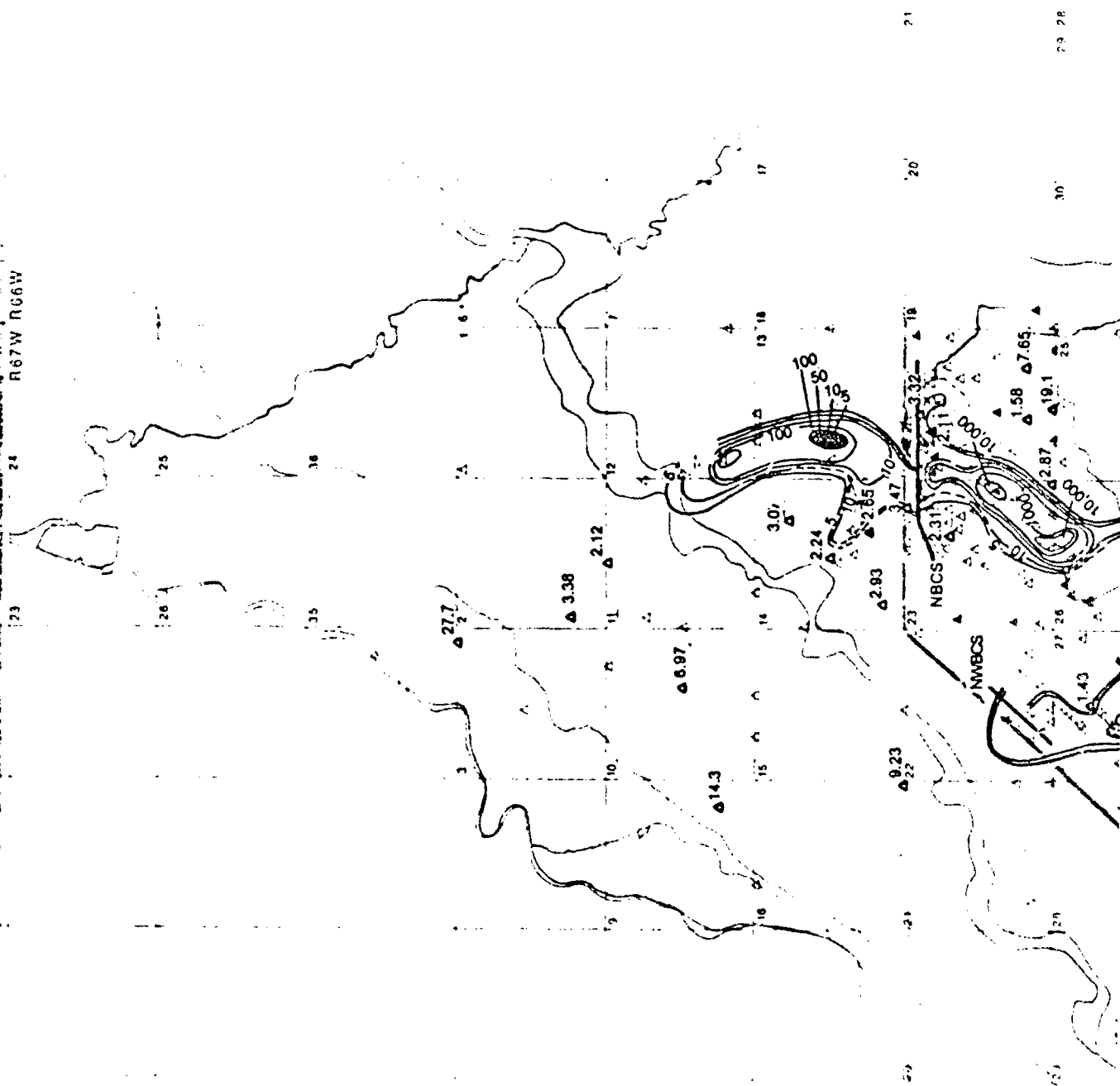


**SURFACE WATER QUALITY FALL 85-FALL 87; MULTIPLE
DETECTED COMPOUNDS**

Prepared for:

**U.S. Army Program Manager's Office
For Rocky Mountain Arsenal**

Aberdeen Proving Ground, Maryland



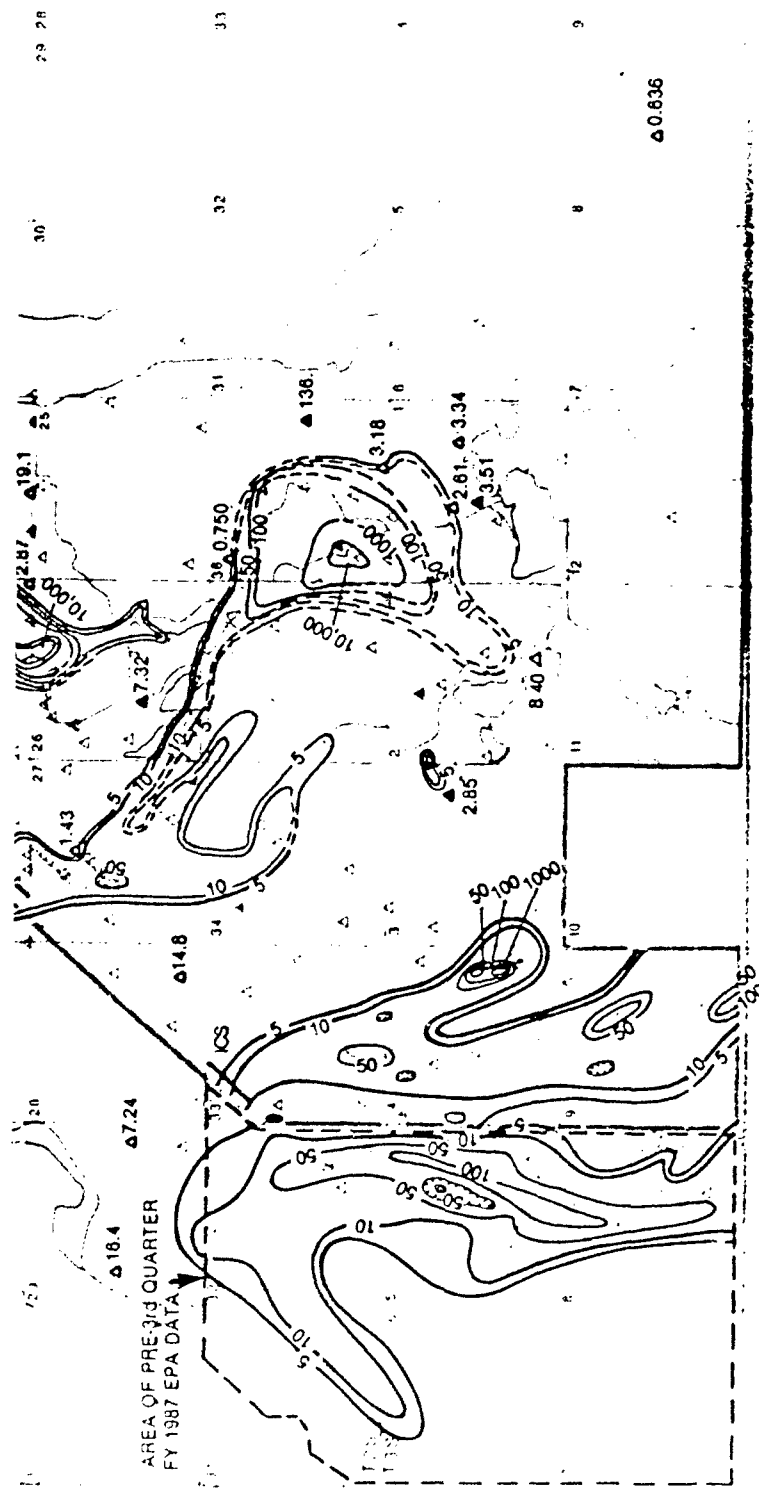


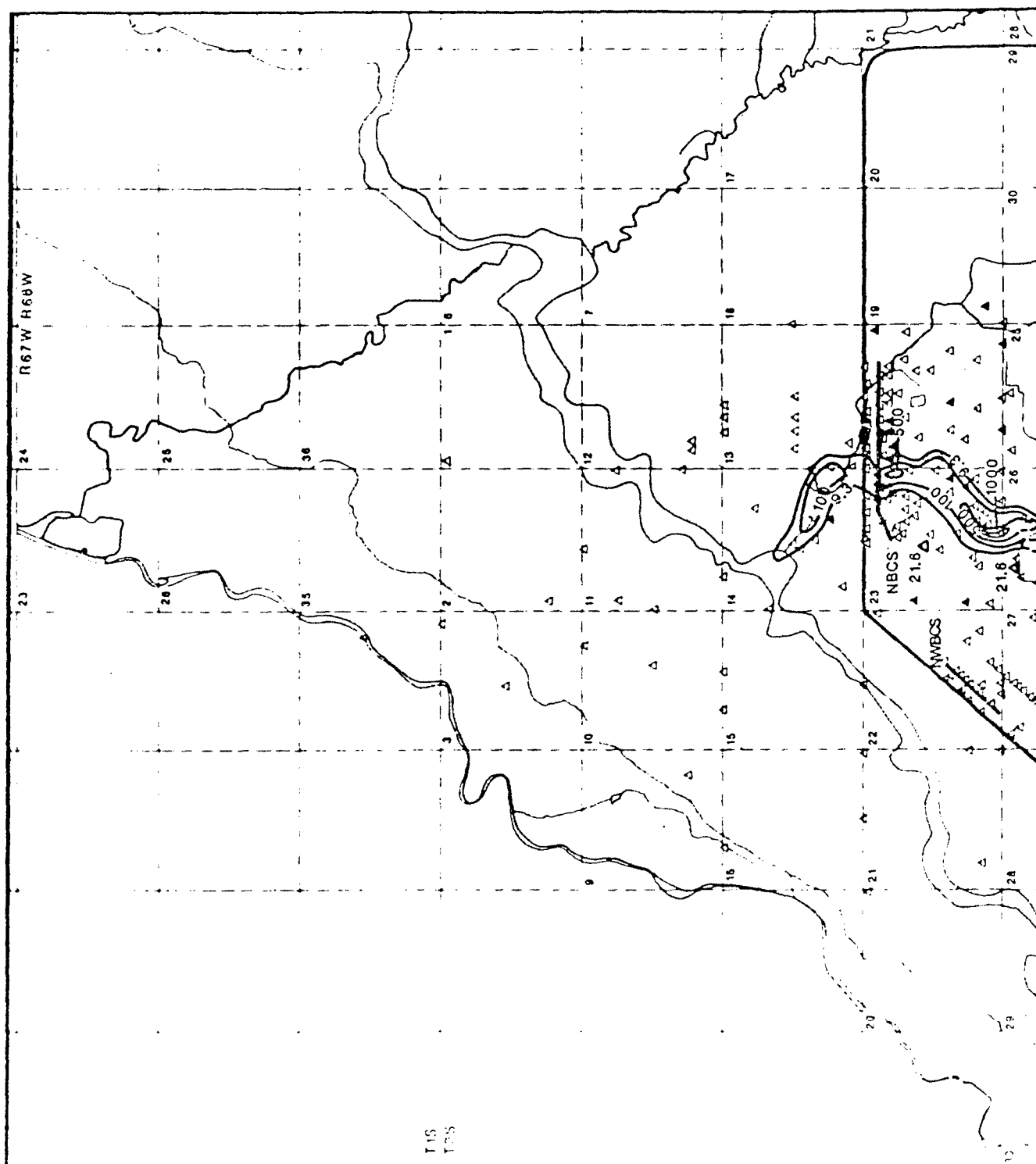
Figure 3.3

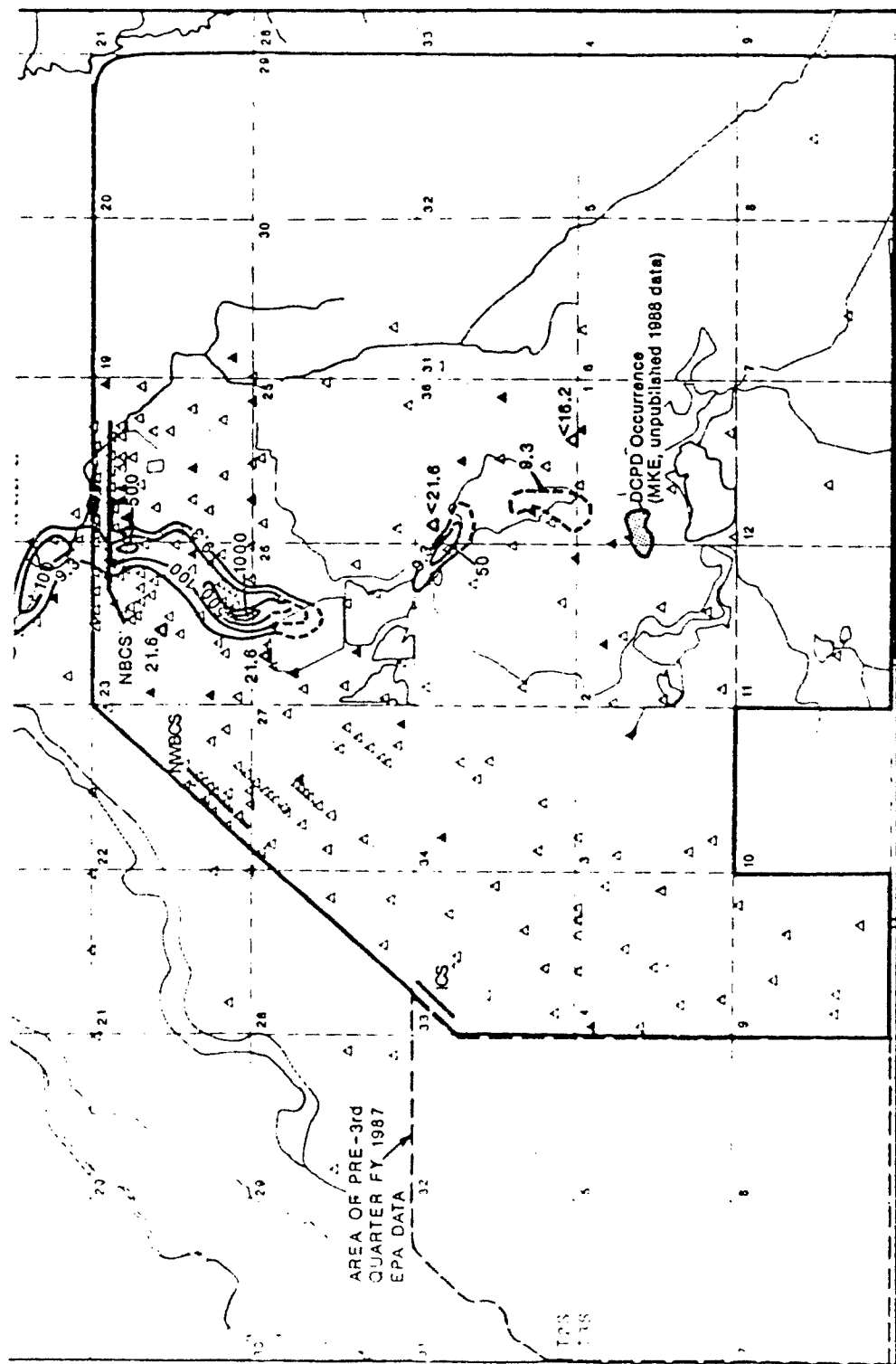
SUMMED VOLATILE HALOGENATED ORGANICS PLUMES UNCONFINED
GROUNDWATER FLOW SYSTEM, 3RD QUARTER, FY 1987

SOURCE: HPL/USE 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland



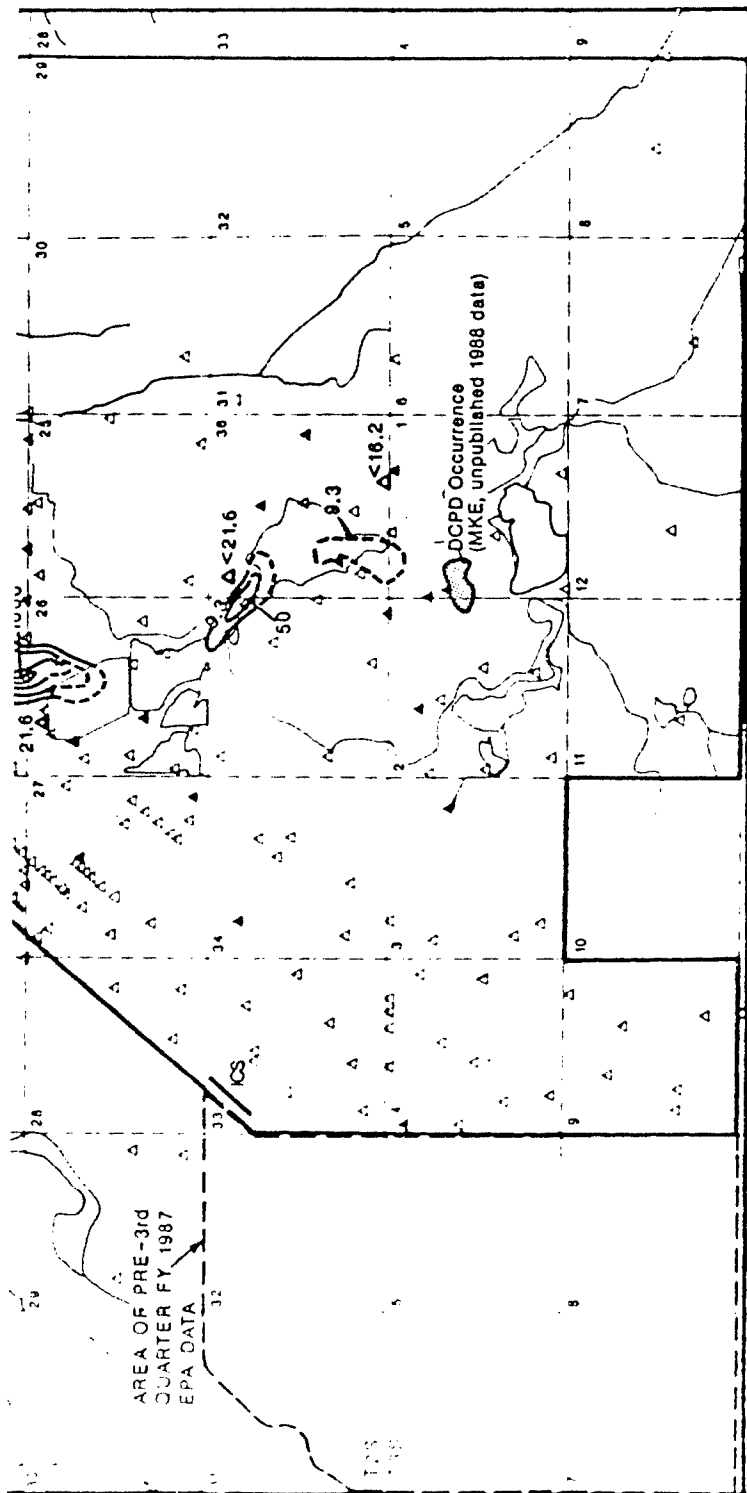


EXPLANATION

- △ Alluvial Well
- ▲ Unconfined Denver Fm. Well
- Isocentration Line, Dashed Where Inferred
- △ 255 Isolated Alluvial Detection or Detection Less Than Highest CRL, 25 ug/l
- CL: 9.3 ug/l
- 250 ug/l
- 500 ug/l
- 1000 ug/l

Figure 3.4

Prepared for:



EXPLANATION

- △ Alluvial Well
- ▲ Unconfined Denver Fm. Well
- Isocentration Line, Casted Where Inferred
- △ 2.85
- △ 9.3 ug/l
- △ 250 ug/l
- △ 500 ug/l
- △ 1000 ug/l
- △ Isolated Alluvial Detection or Detection Less Than Highest CRL, 10 ug/l

CIL: 9.3 ug/l
 250 ug/l
 500 ug/l
 1000 ug/l



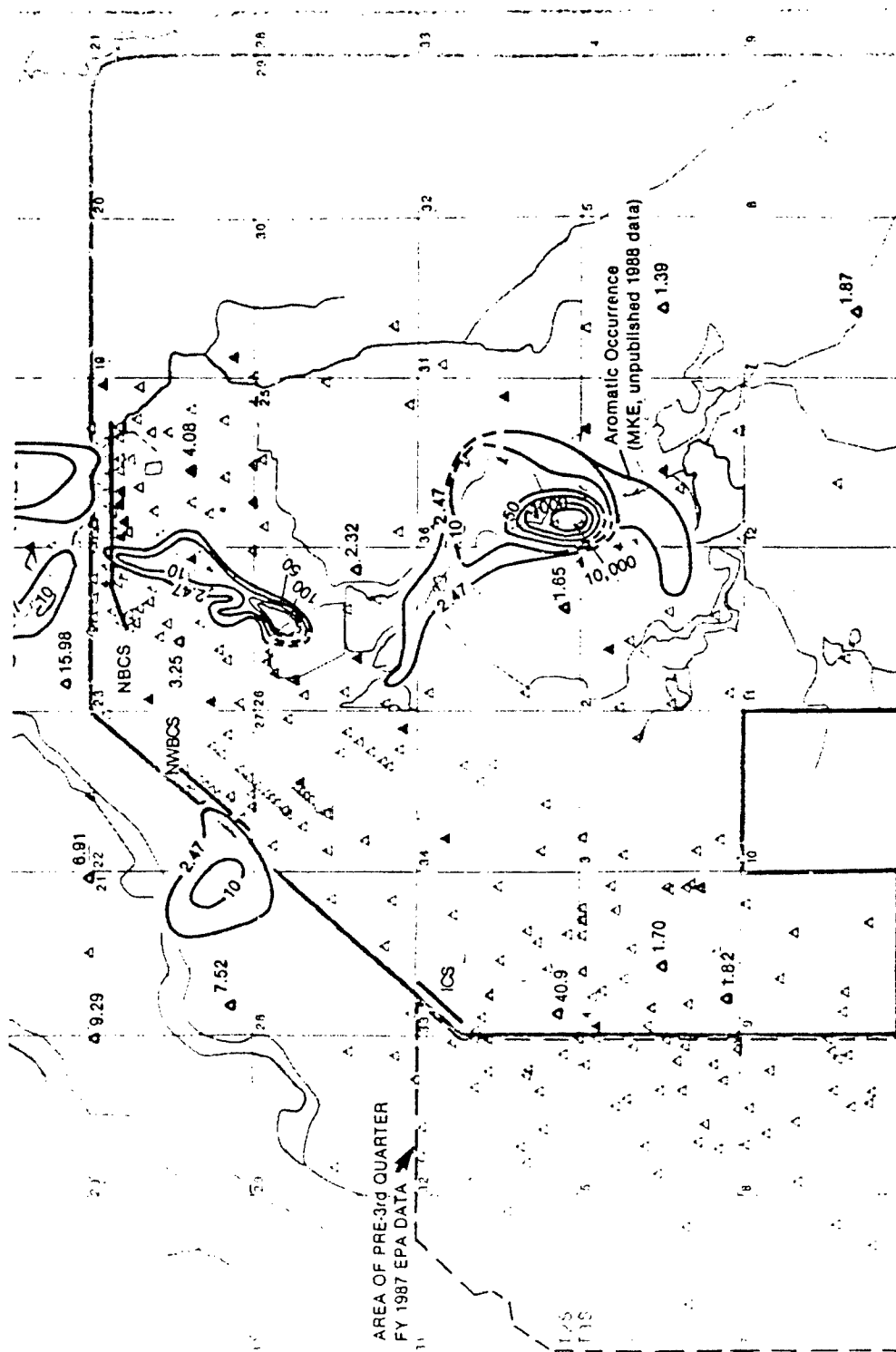
Figure 3.4

DICYCLOPENTADIENE PLUMES UNCONFINED GROUNDWATER FLOW SYSTEM, 3RD QUARTER, FY 1987

SOURCE: MKA, 1988

Prepared for:
 U.S. Army Program Manager's Office
 For Rocky Mountain Arsenal
 Aberdeen Proving Ground, Maryland

515
521



NOTE: Summed Volatile Aromatics Include Benzene, Chlorobenzene, Toluene, Ethylbenzene, M-Xylene, and O- and P-Xylenes.

EXPLANATION

- △ Alluvial Well
- ▲ Unconfined Denver Fm. Well
- Isoconcentration Line, Dashed Where Inferred
- △ 2.65 Isolated Alluvial Detection or Concentration Less Than Highest CRL, In ug/l
- CL: 2.47 ug/l
- 10 ug/l
- 50 ug/l
- 100 ug/l
- 1000 ug/l
- 10,000 ug/l

Figure 3.5

Prepared for:

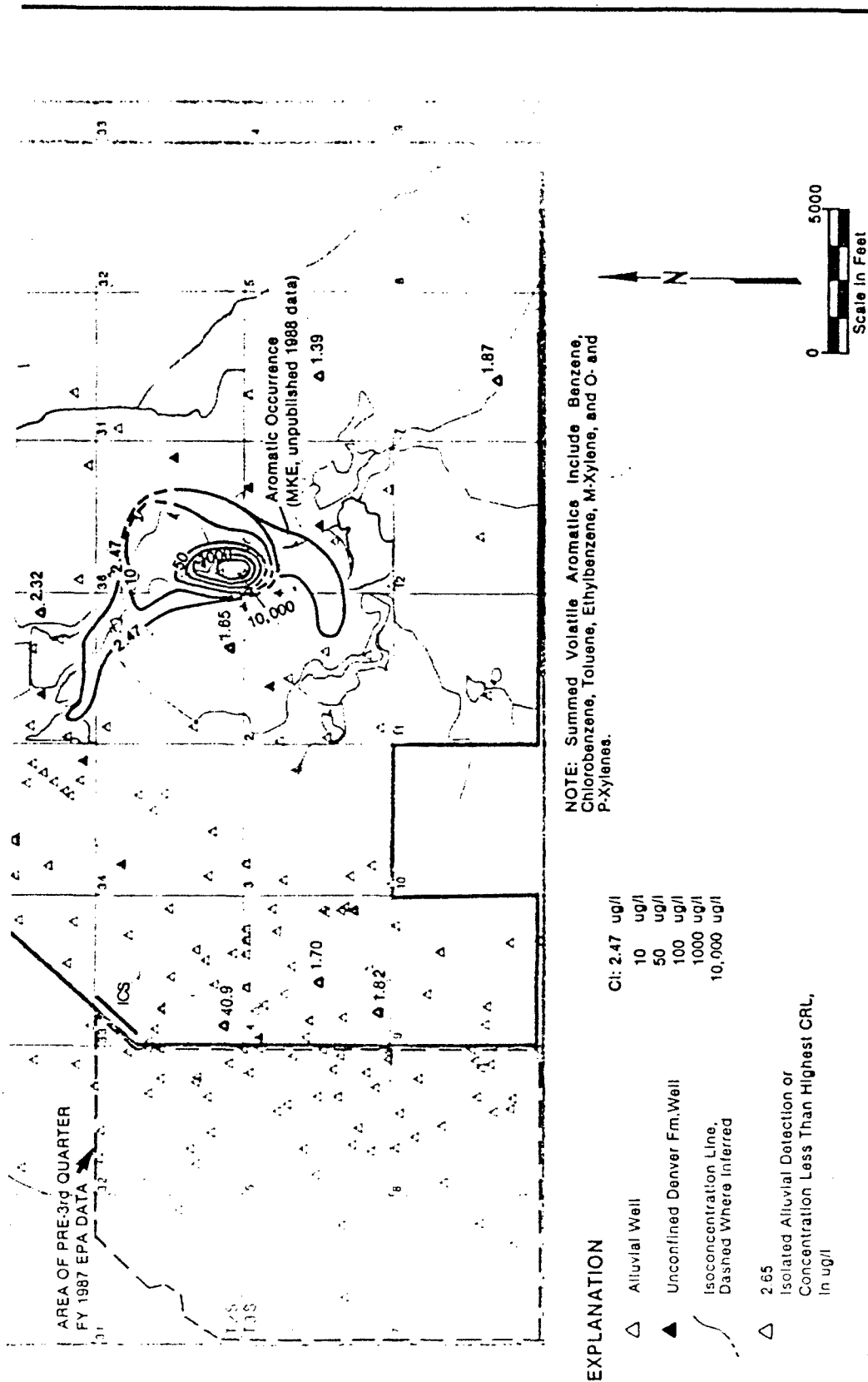


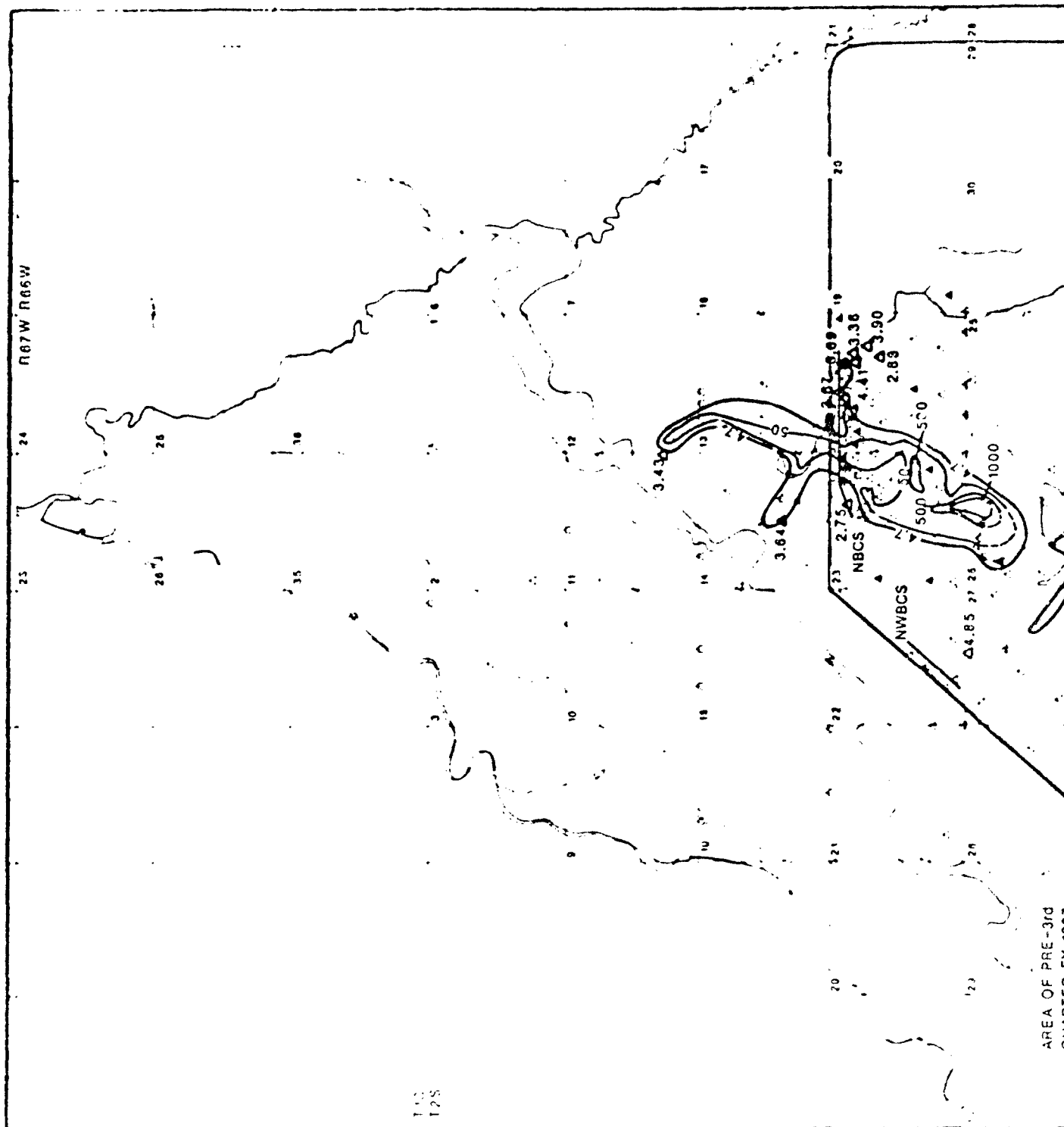
Figure 3.5

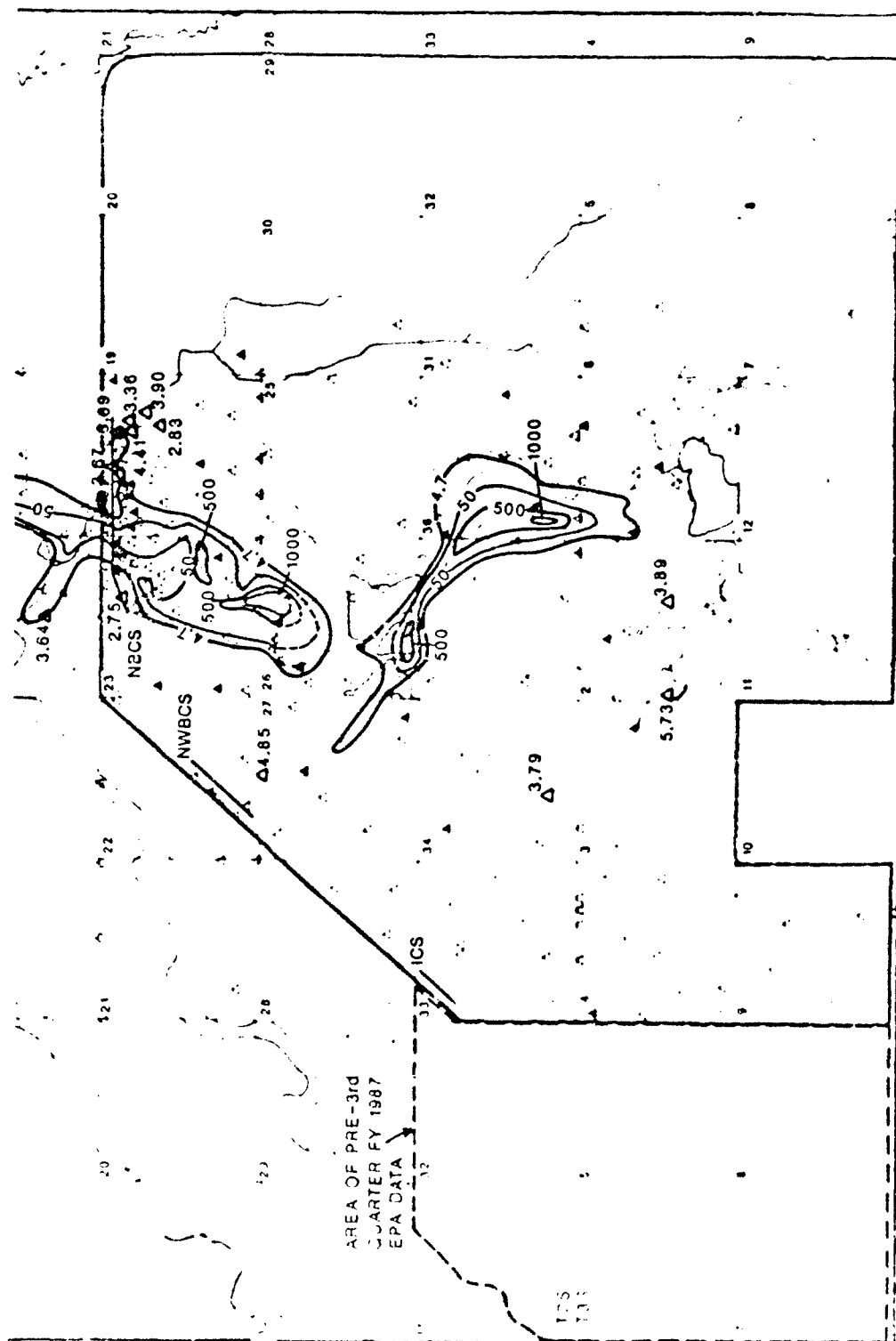
SUMMED VOLATILE AROMATICS PLUMES UNCONFINED GROUNDWATER
FLOW SYSTEM, 3RD QUARTER, FY 1987

SOURCE: HLA, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland





EXPLANATION

Cl: 4.7 ug/l
 50 ug/l
 500 ug/l
 1000 ug/l

A Aerial Well
 B Uncontaminated Center Pm Well

C Contamination Line,
 Contained Where Indicated

D 265
 E Isolated Aerial Detection or
 Detection less than highest CRL

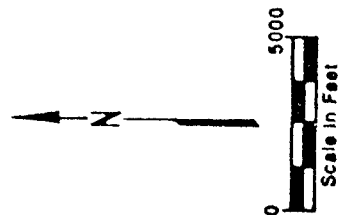
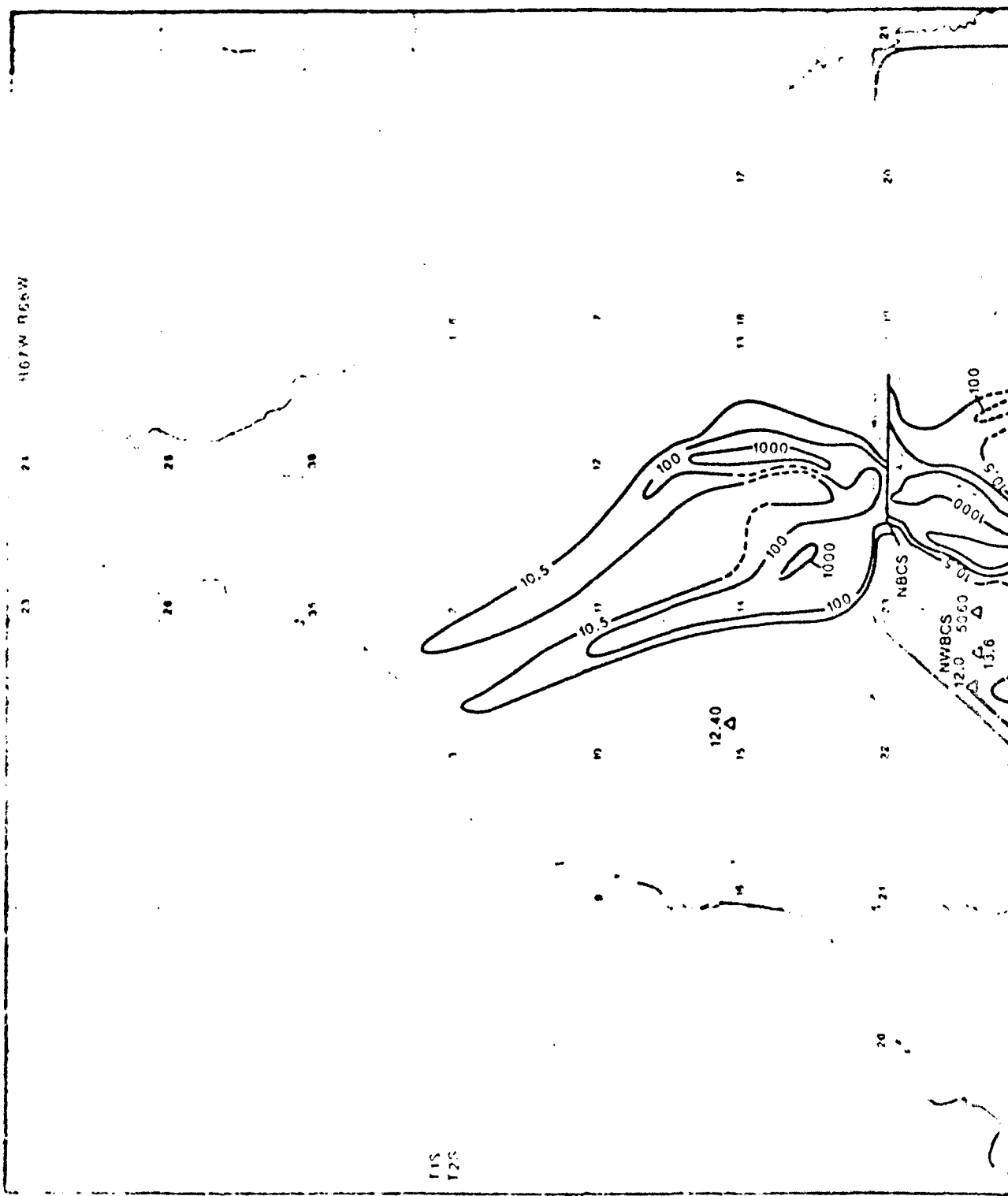
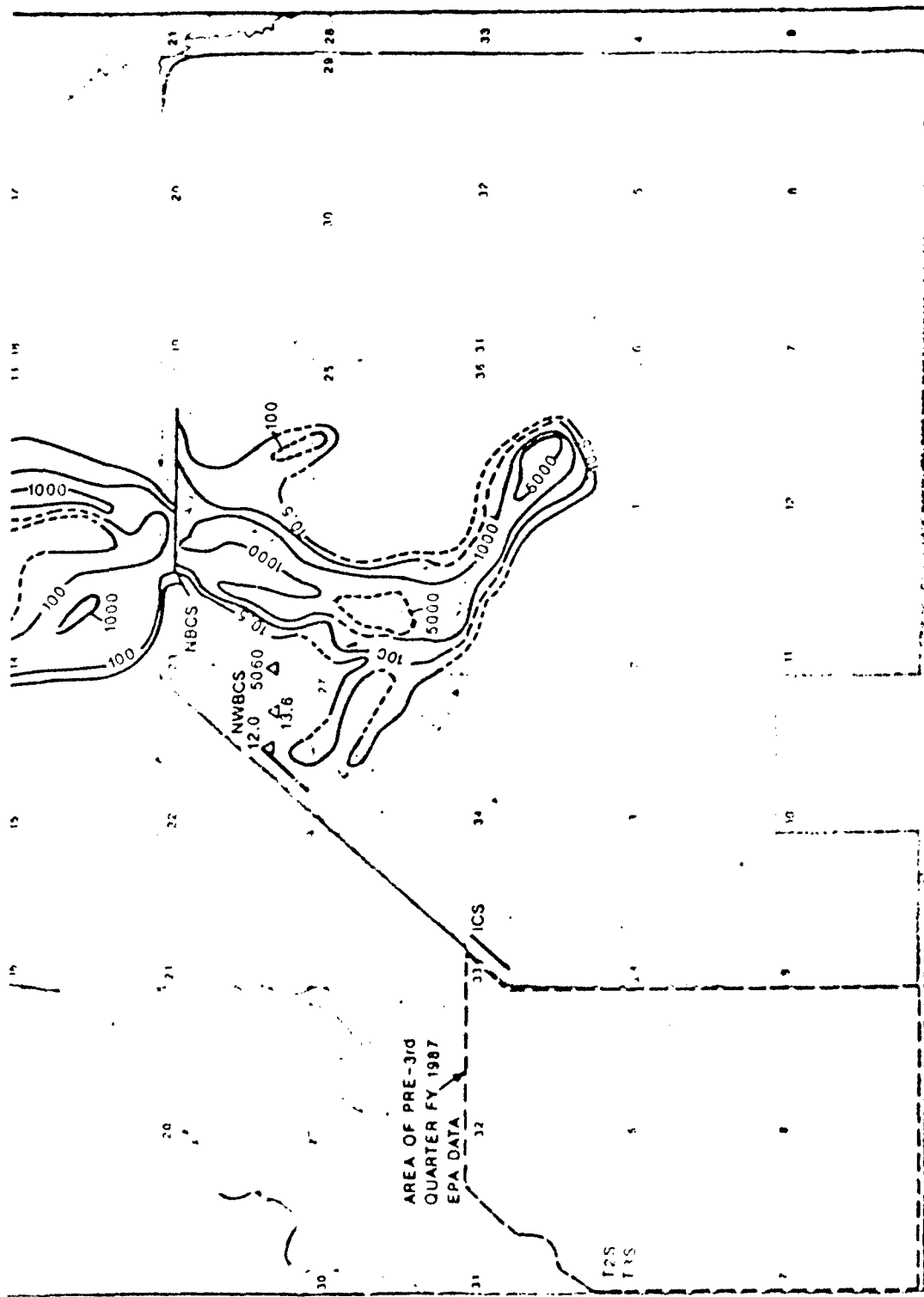


Figure 3.6

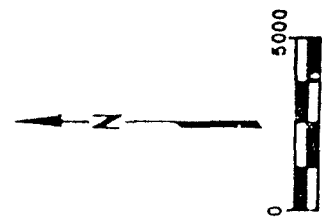
Prepared for:

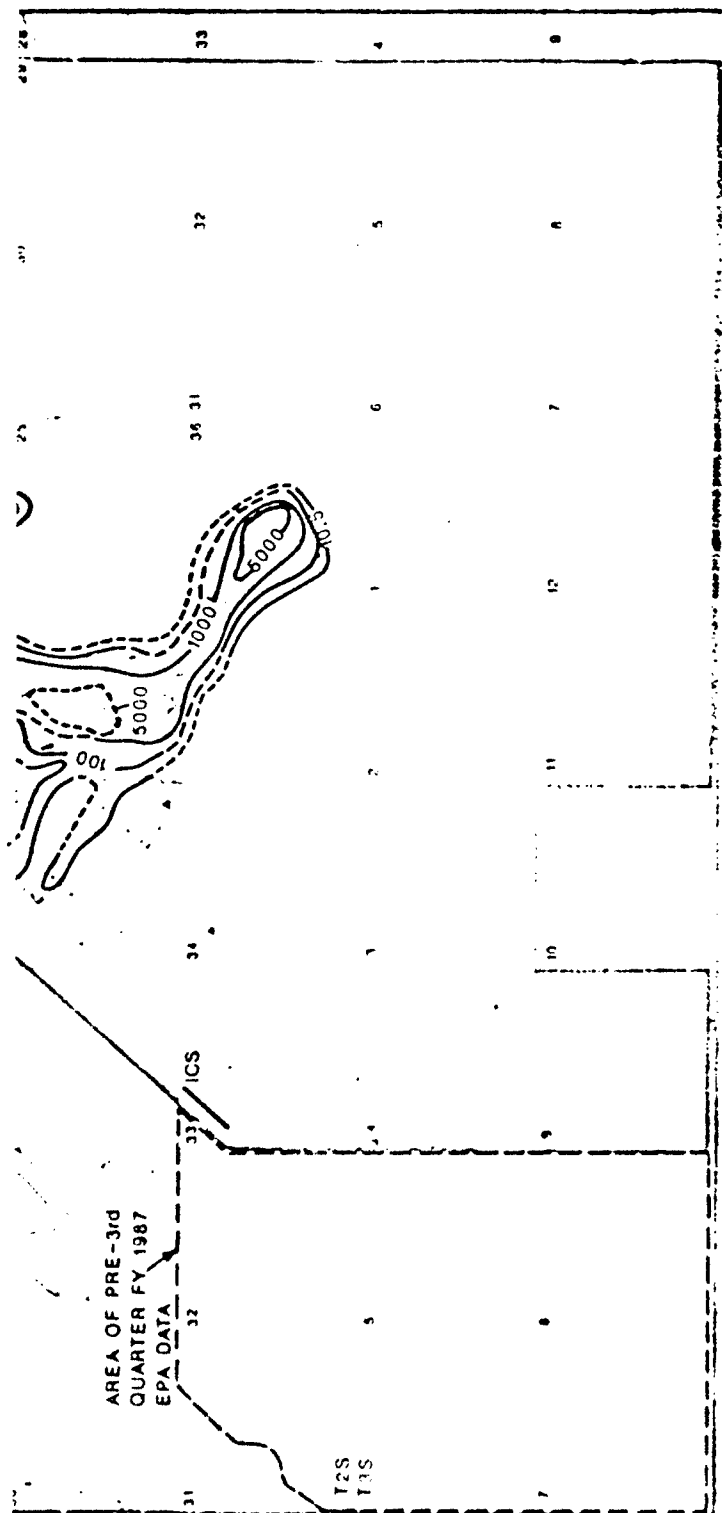




EXPLANATION

- △ Alluvial Well
- ▲ Unconfined Denver Fm. Well
- Isoconcentration Line, Dashed Where Inferred
- △ 265 Isolated Alluvial Detection or Detection Less Than Highest CRL, in ug/l
- CL: 10.5 ug/l
- 100 ug/l
- 1000 ug/l
- 5000 ug/l





EXPLANATION

- △ Alluvial Well
- ▲ Unconfined Denver Fm. Well
- Isoconcentration Line.
Dashed Where Inferred
- △ 2.65
Isolated Alluvial Detection or
Detection Less Than Highest CRL
in ug/l
- CI: 10.5 ug/l
100 ug/l
1000 ug/l
5000 ug/l

Figure 3.7

DIISOPROPYLMETHYLPHOSPHONATE PLUMES UNCONFINED GROUND-WATER FLOW SYSTEM, THIRD QUARTER, FY 1987

SOURCE HLA, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal

Aberdeen Proving Ground, Maryland

R67W R66W

23

24

25

26

35

36

118
126

10

11

12

13

14

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16

17

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19

20

21

22

23

24

25

26

27

28

NBCS

NWBCS

50.147

20.0

51.0

27.26

28

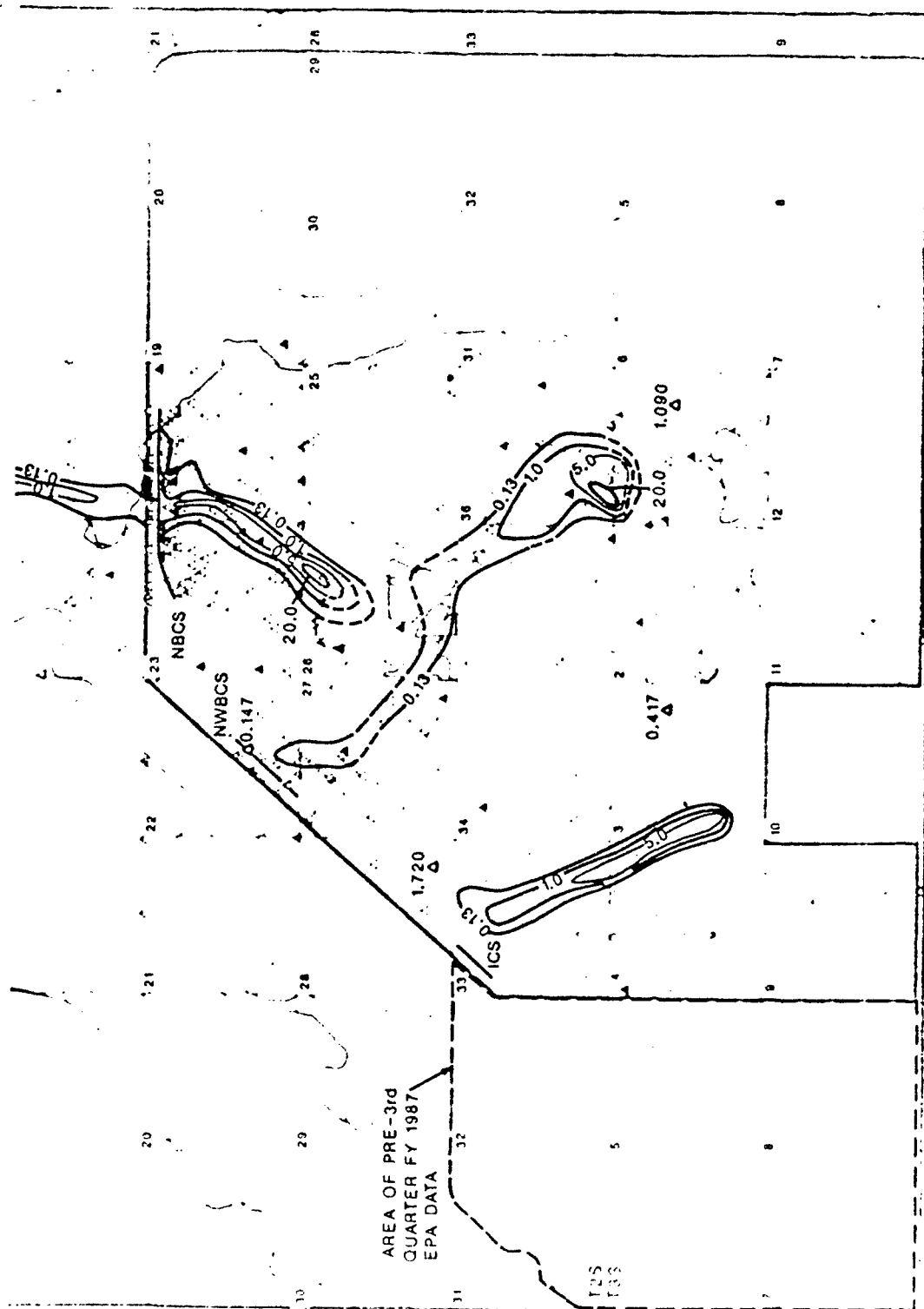
29

30

31

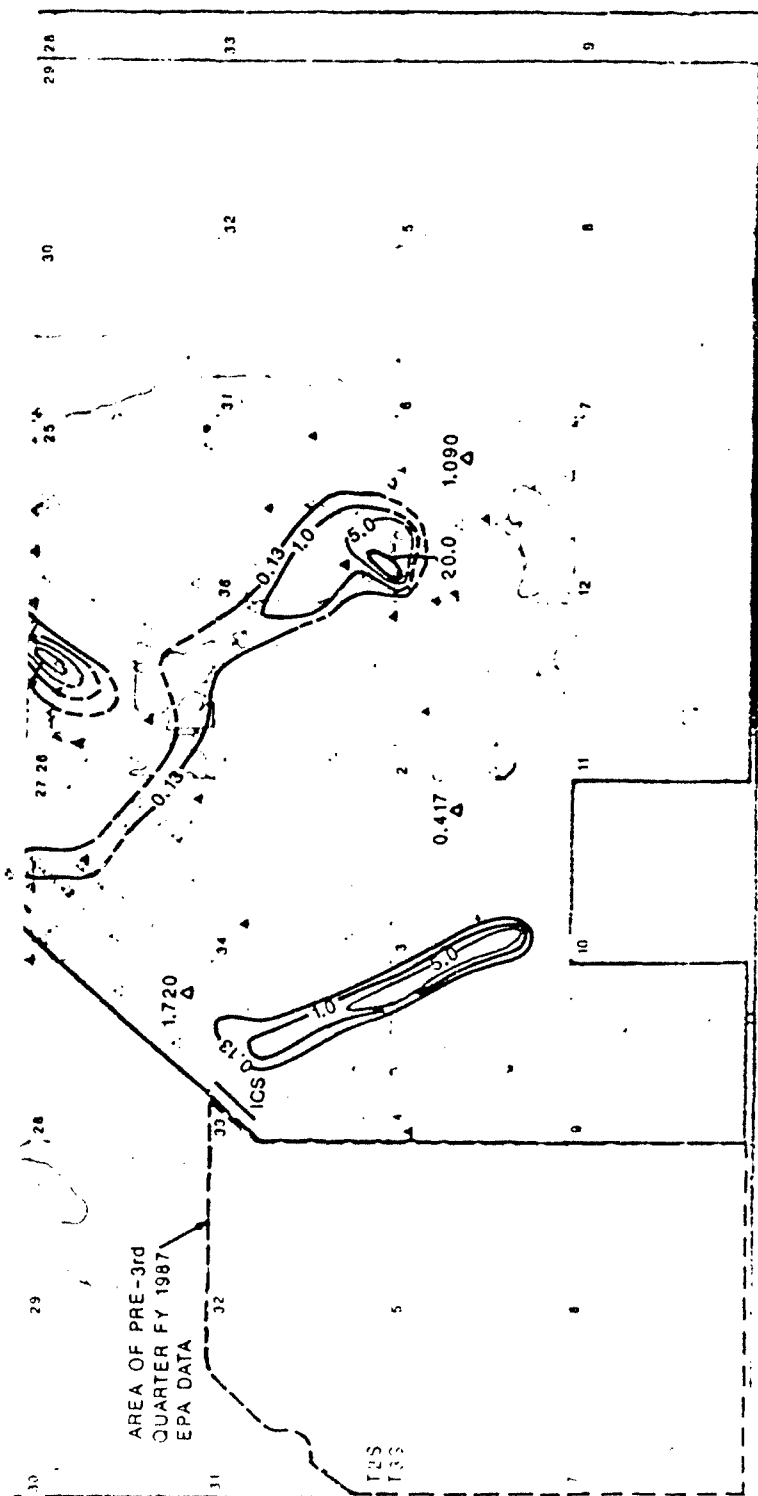
32

33



EXPLANATION

- △ Alluvial Well
 - ▲ Unconfined Denver Fm. Well
 - Isoconcentration Line, Dashed Where Inferred
 - △ 2.65 Isolated Alluvial Detection or Detection Less Than Highest CRL, in ug/l
- CIL: 0.13 ug/l
 1.0 ug/l
 5.0 ug/l
 20.0 ug/l



EXPLANATION

- △ Alluvial Well
- ▲ Unconfined Denver Fm. Well
- Isoconcentration Line, Dashed Where Inferred
- △ 2.65 Isolated Alluvial Detection or Detection Less Than Highest CRL, In ug/l

C1: 0.13 ug/l
1.0 ug/l
5.0 ug/l
20.0 ug/l

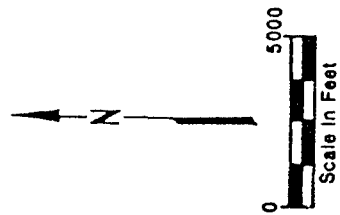
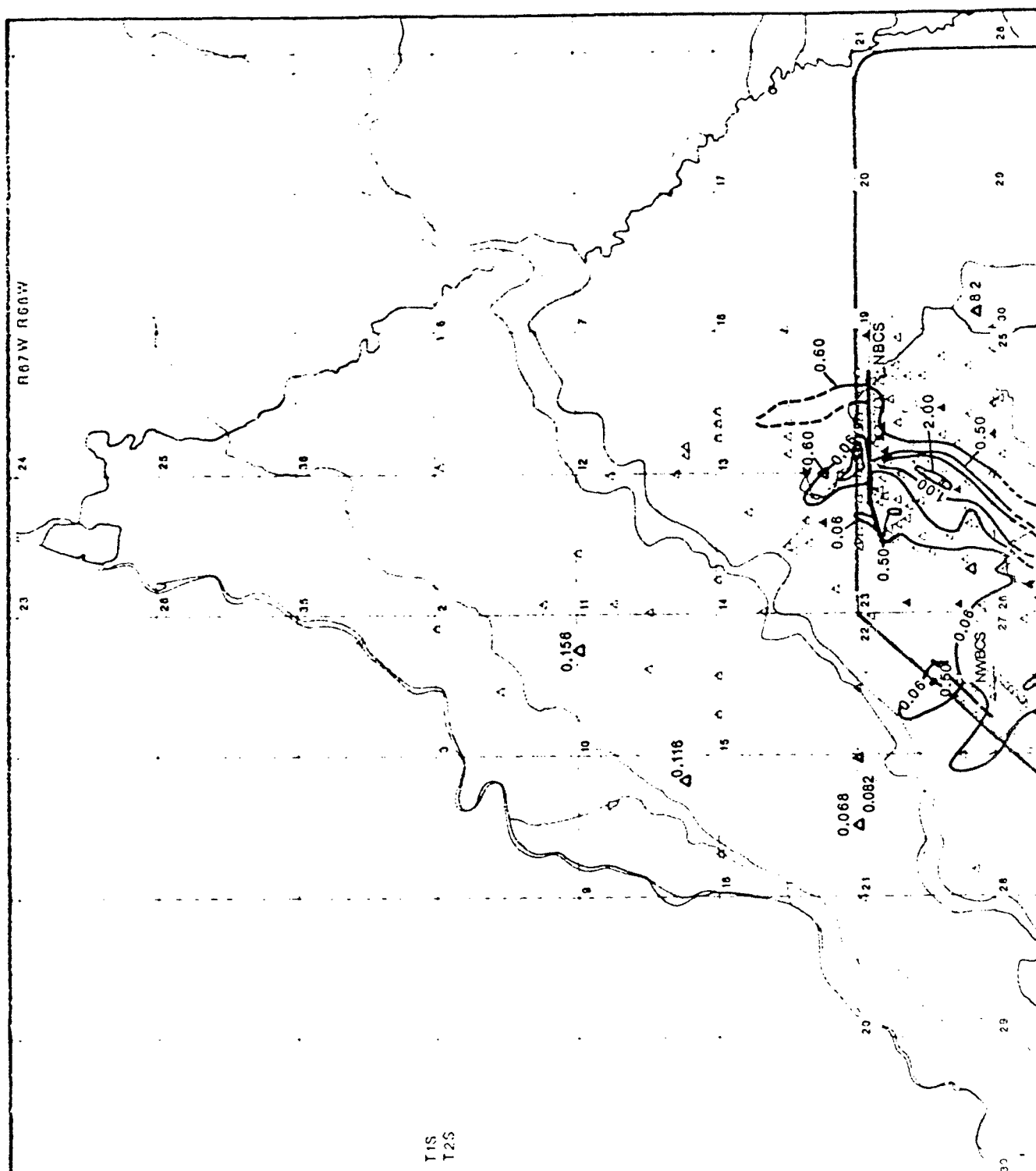


Figure 3.8

DIBROMOCHLOROPROPANE PLUMES UNCONFINED GROUNDWATER FLOW SYSTEM, 3RD QUARTER, FY 1987

SOURCE: HLA, 1989

Prepared for:
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T1S
T2S

R67W R68W

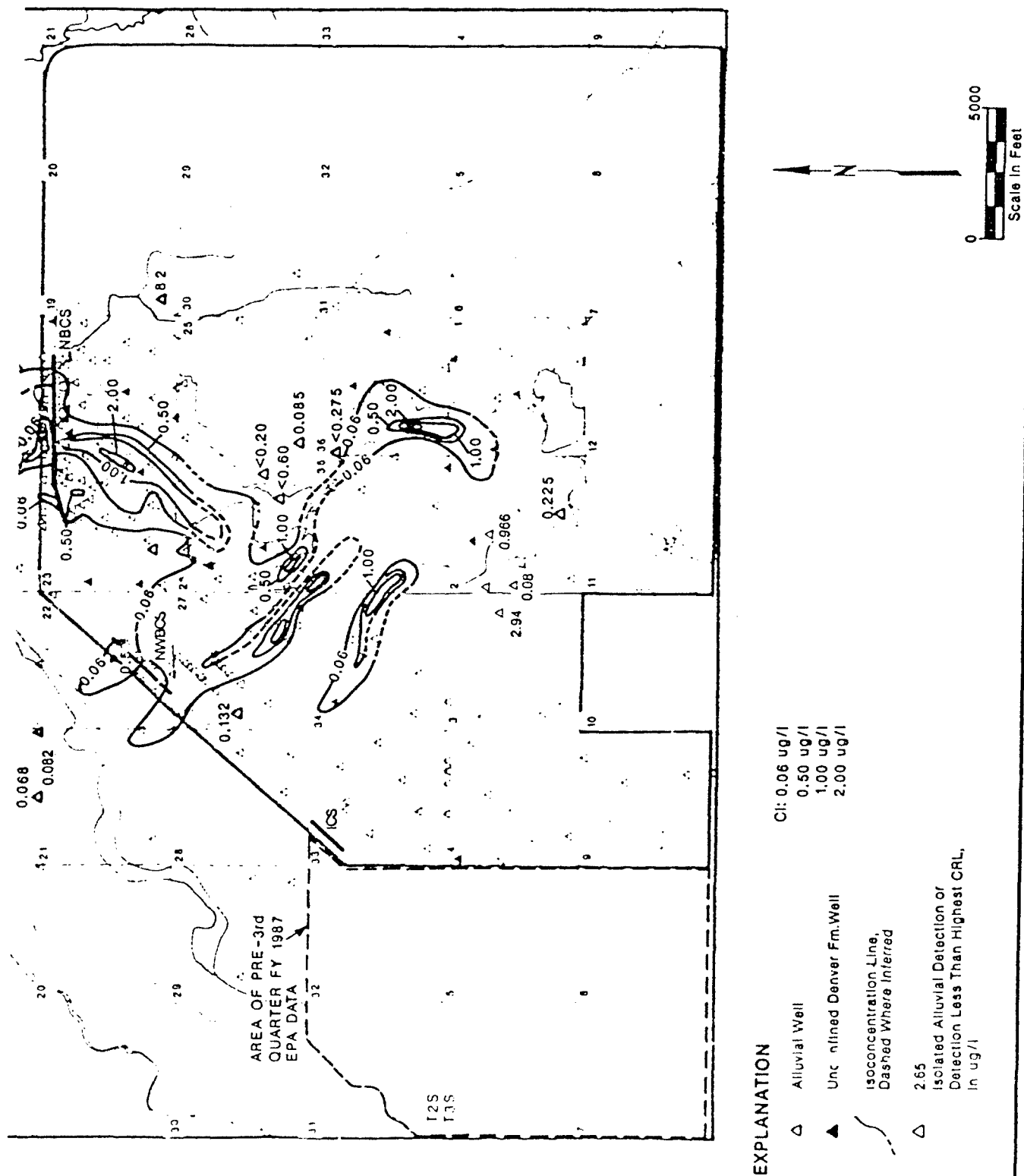
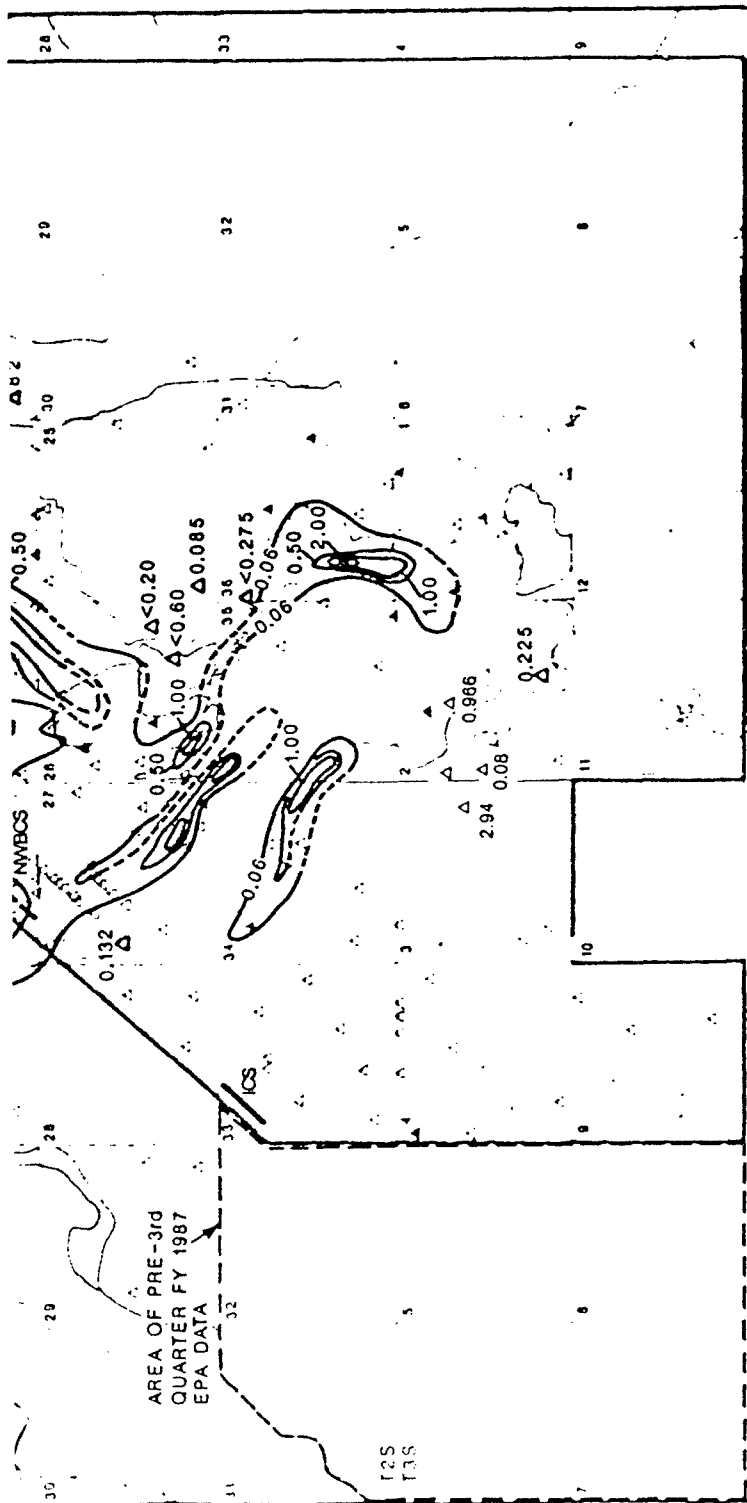


Figure 3.9

DIEHRIN PLUMES UNCONFINED GROUNDWATER FLOW SYSTEM
3RD QUARTER, FY 1987

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal



EXPLANATION

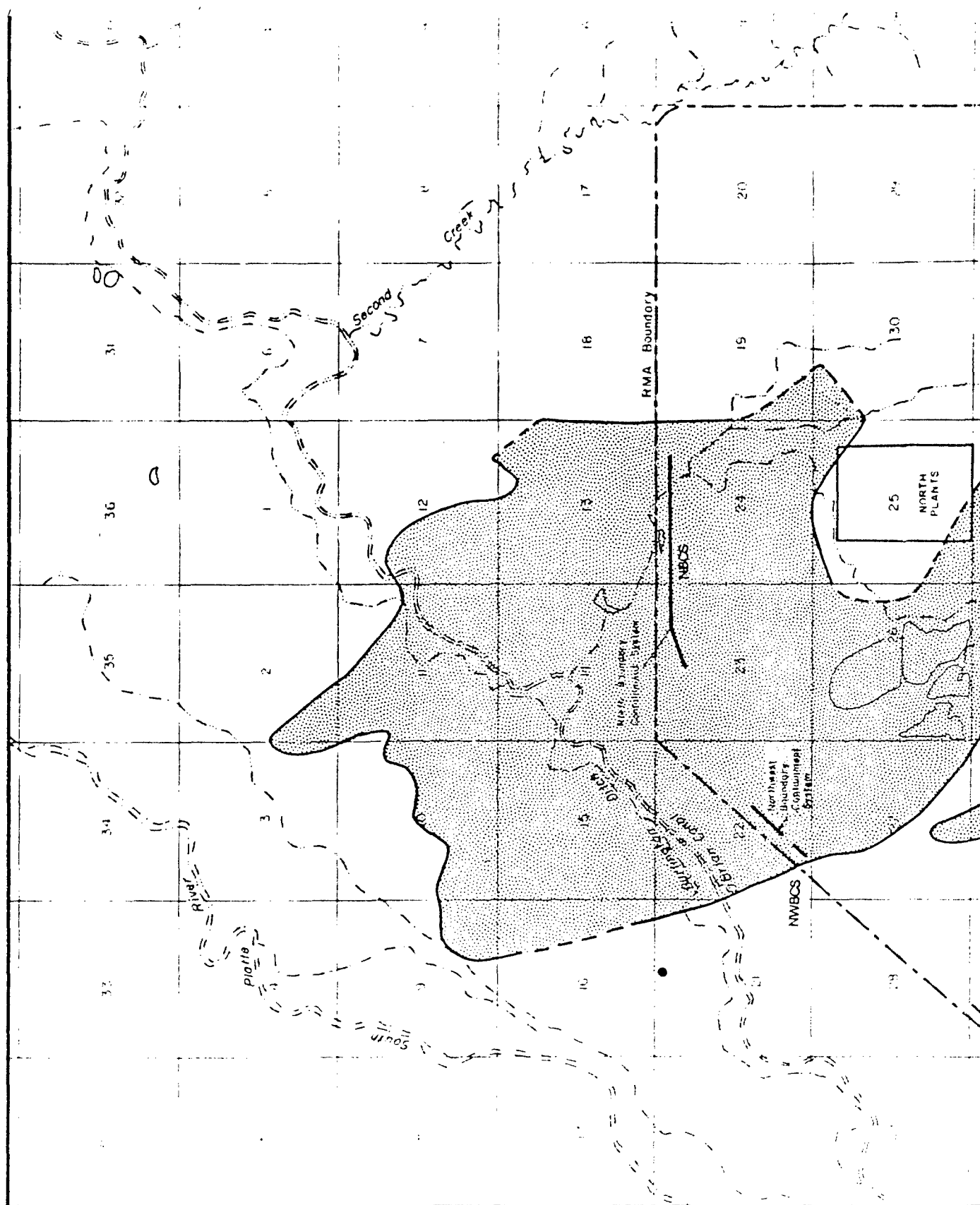
- △ Alluvial Well
- ▲ Unconfined Denver Fm. Well
- Isoconcentration Line, Dashed Where Inferred
- △ 2.65 Isolated Alluvial Detection or Detection Less Than Highest CRL, In ug/l

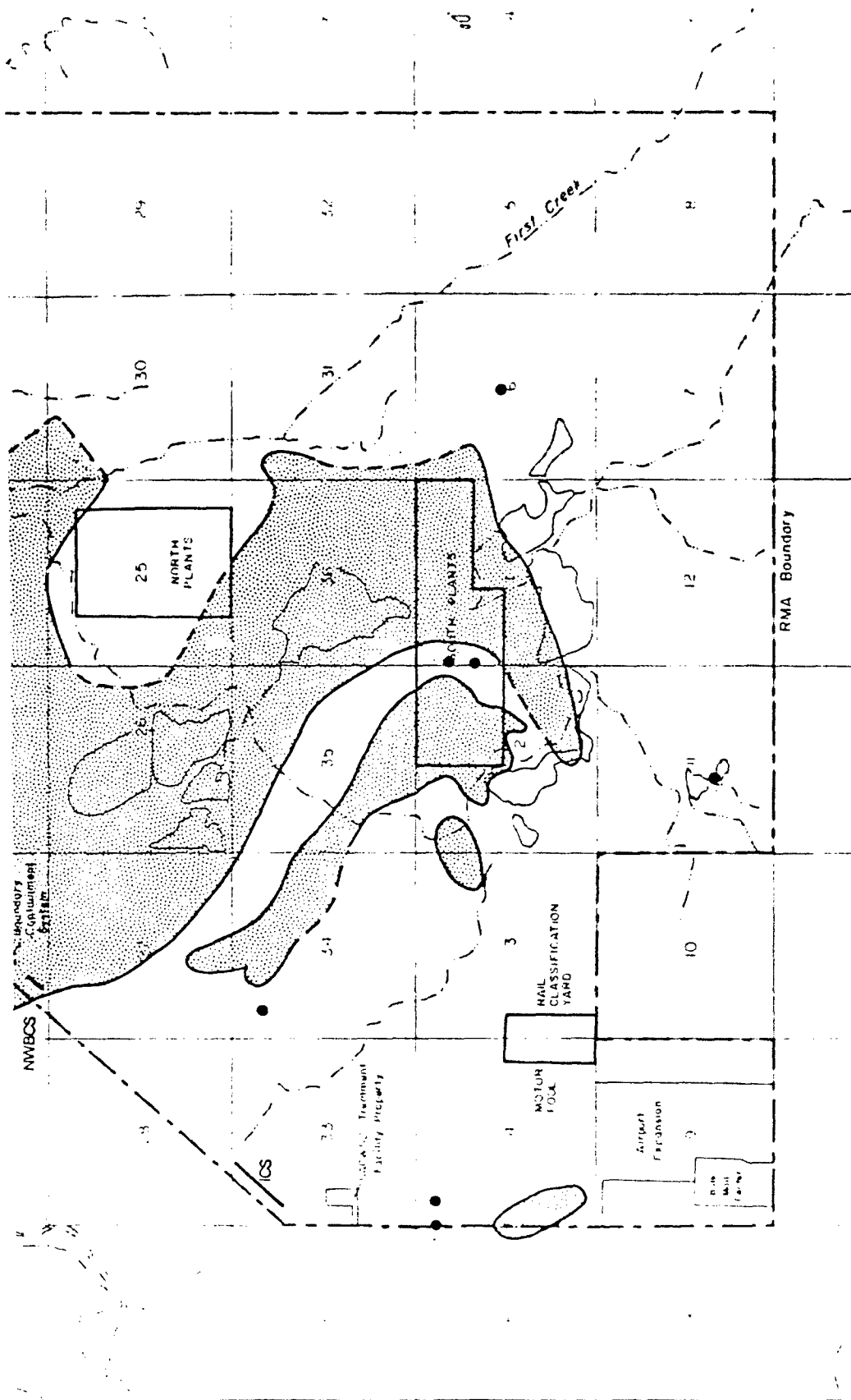
Figure 3.9

DIELDRIN PLUMES UNCONFINED GROUNDWATER FLOW SYSTEM
3RD QUARTER, FY 1987

SOURCE: HLA, 1988

Prepared for:
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For Rocky Mountain Arsenal
Aberdeen Proving Ground, Maryland





Prepared for:

Program Manager's Office for
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Aberdeen Proving Ground, Maryland

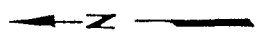
FIGURE 3.10

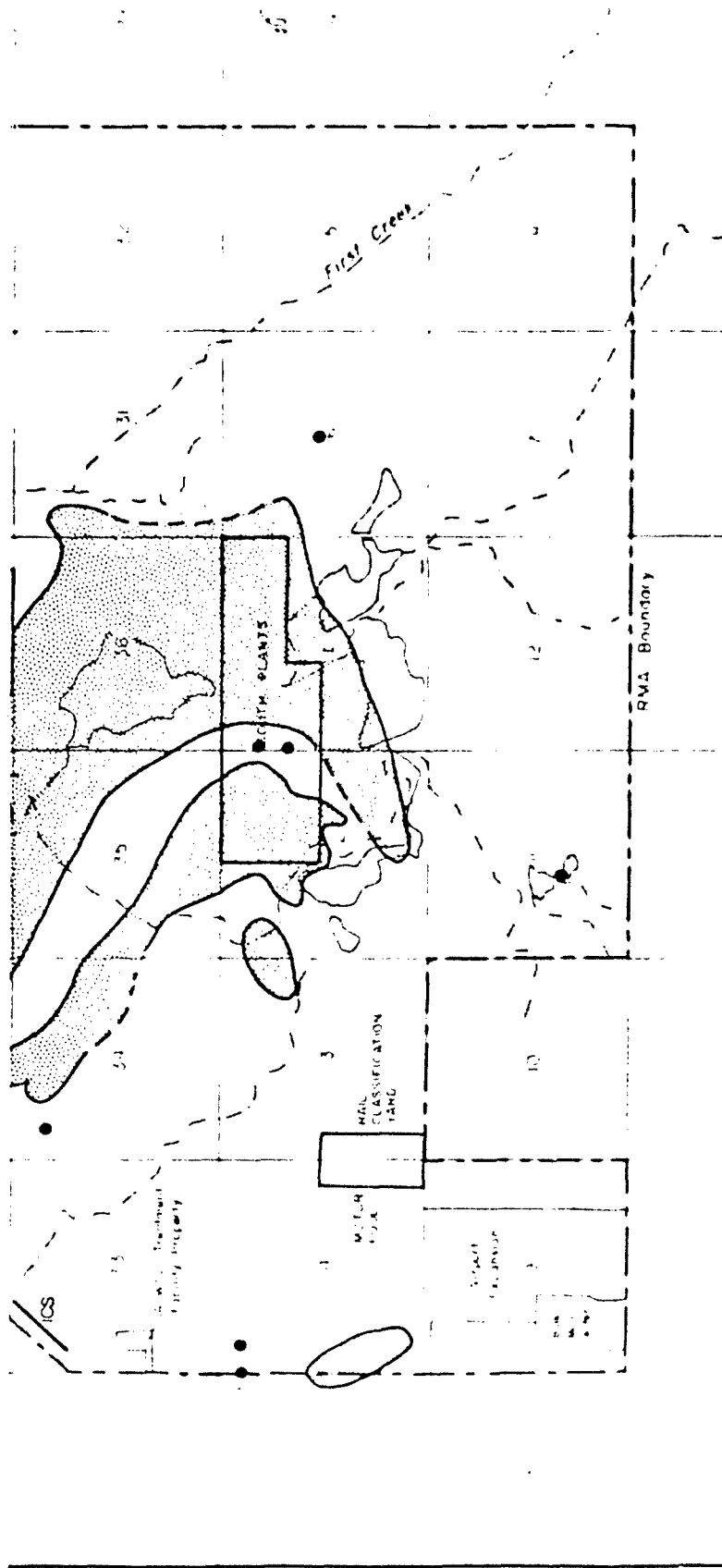
Areal Extent of Inorganic Analytes in

Explanation

Extent of inorganic analytes

Isolated Detection





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FIGURE 3.10

Areal Extent of Inorganic Analytes in
Unconfined Flow System

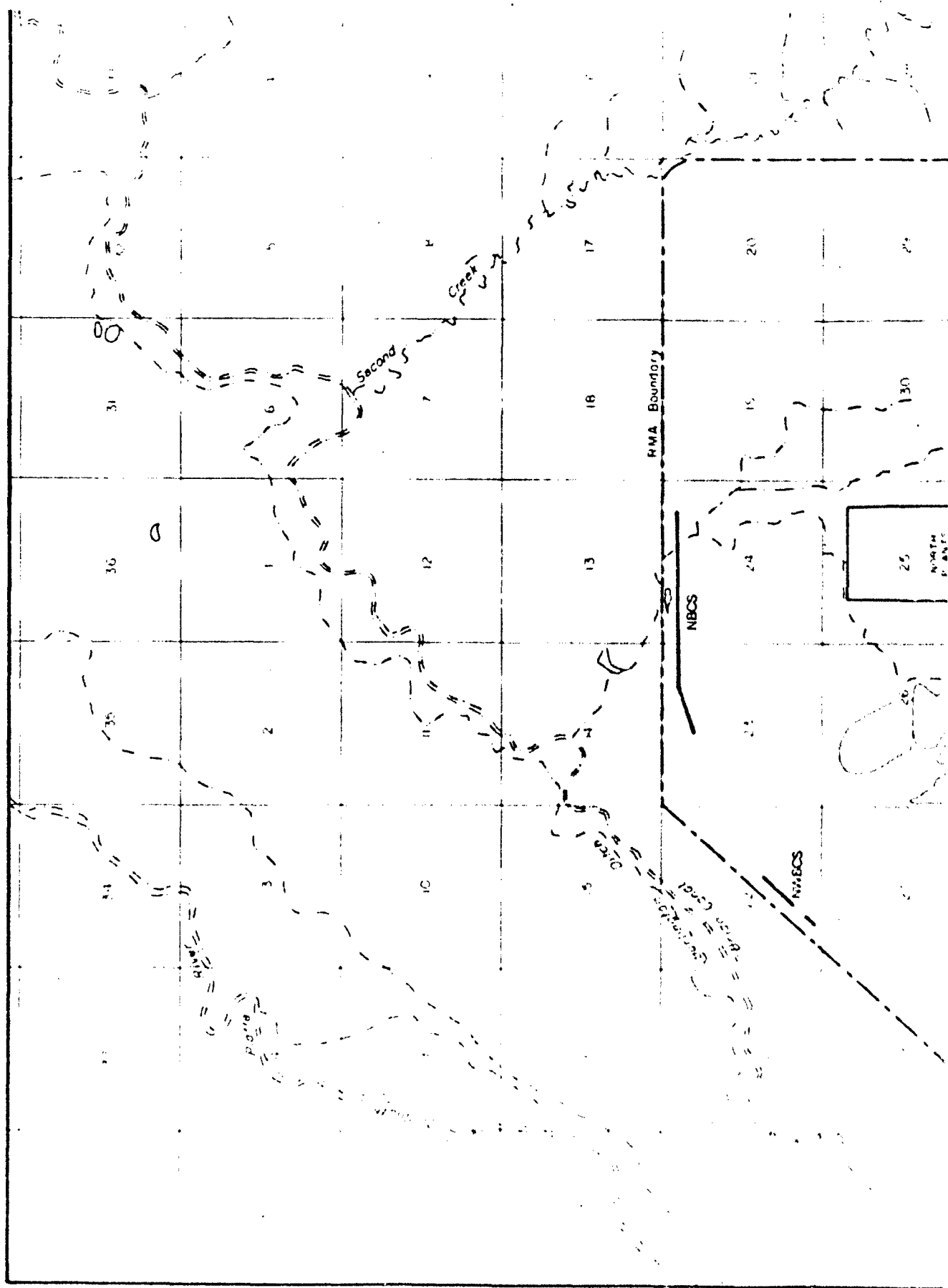
Prepared by: R.L. Stollar & Associates Inc.

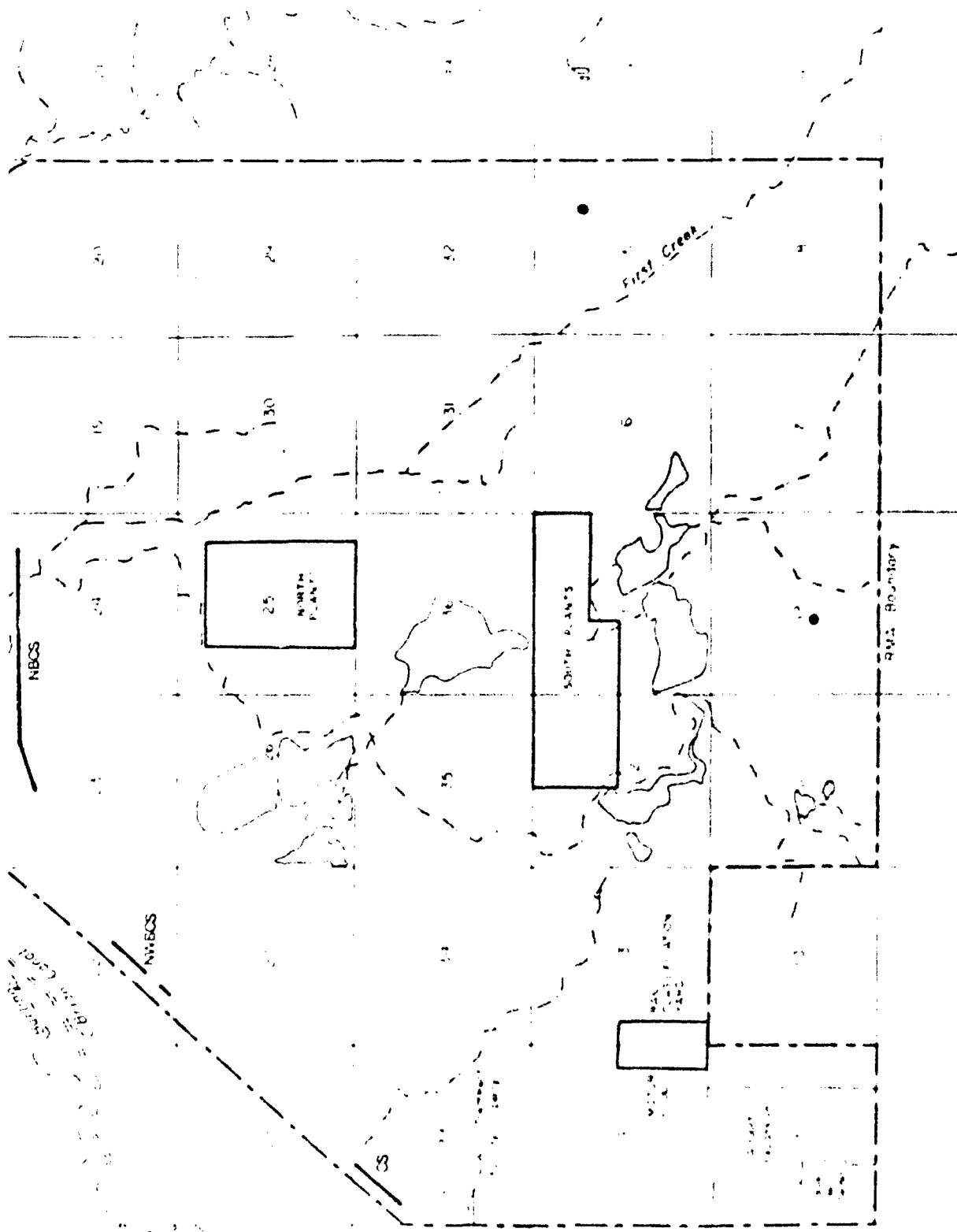
Explanation

Extent of inorganic analytes

Isolated Detection

Source: Compiled from concentration maps in Appendix D and E.





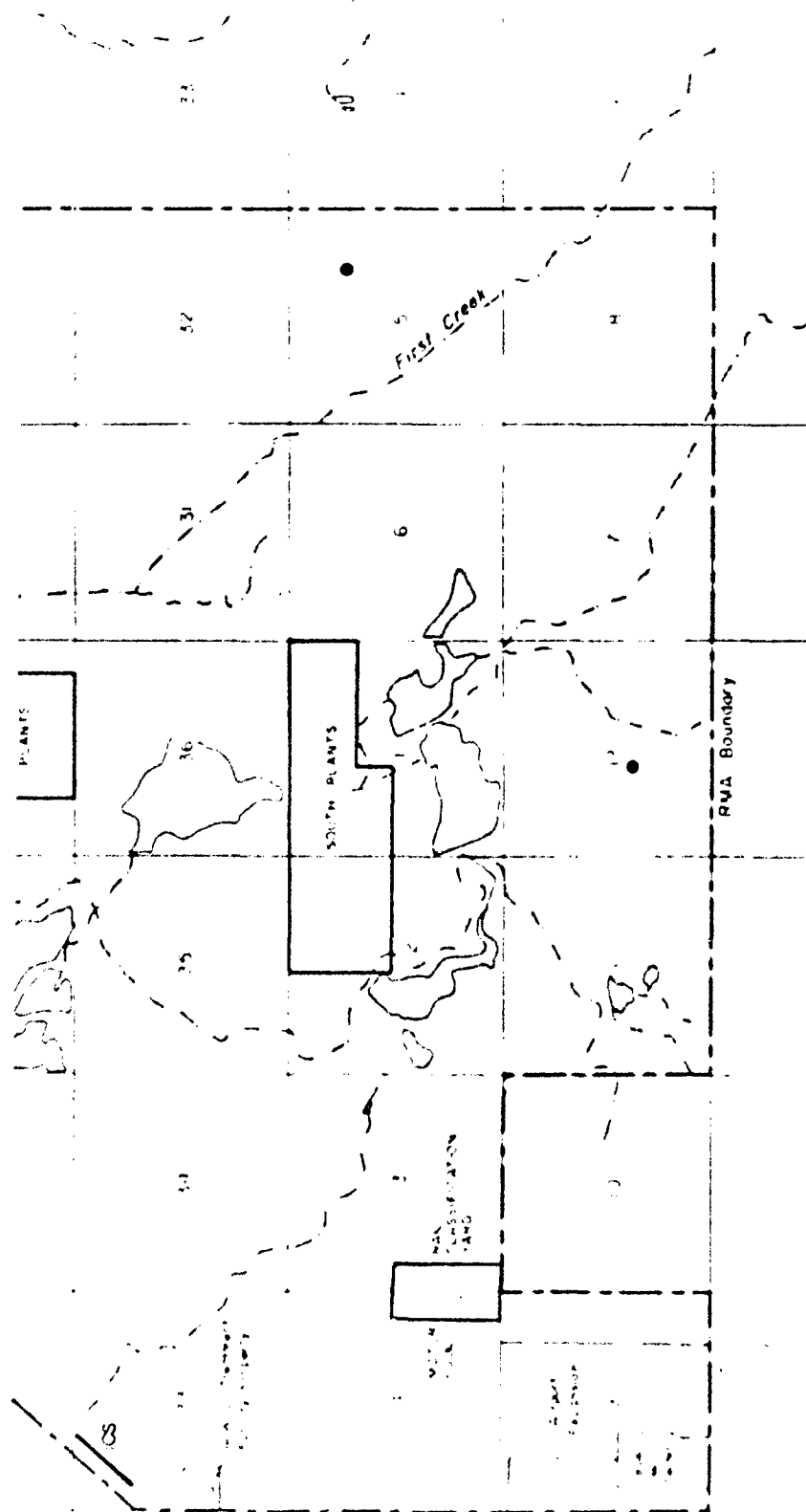
EXPLANATION

● Isolated Detection



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Explanation

● Isolated Detection

Prepared for:

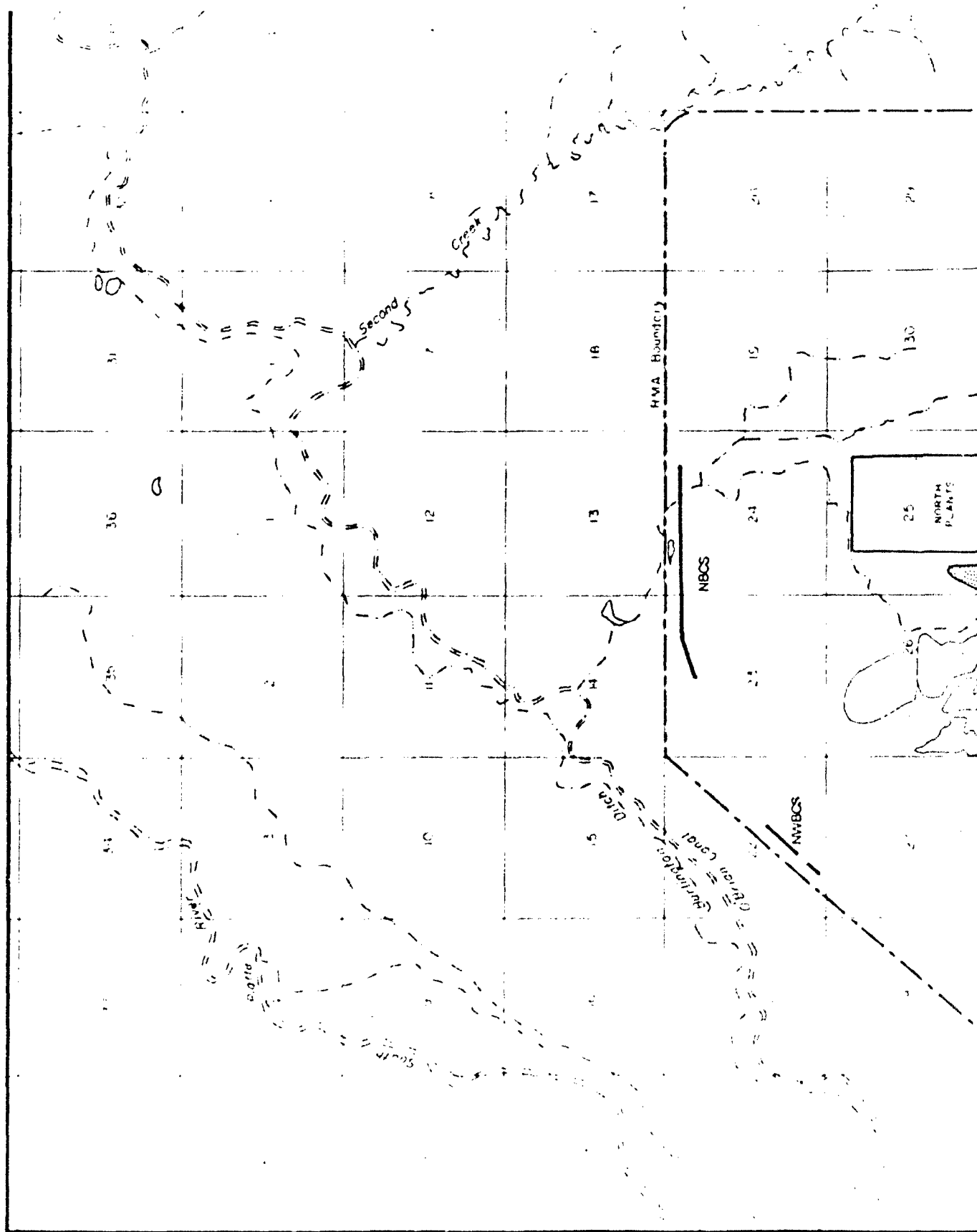
Program Manager's Office for
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Aberdeen Proving Ground, Maryland

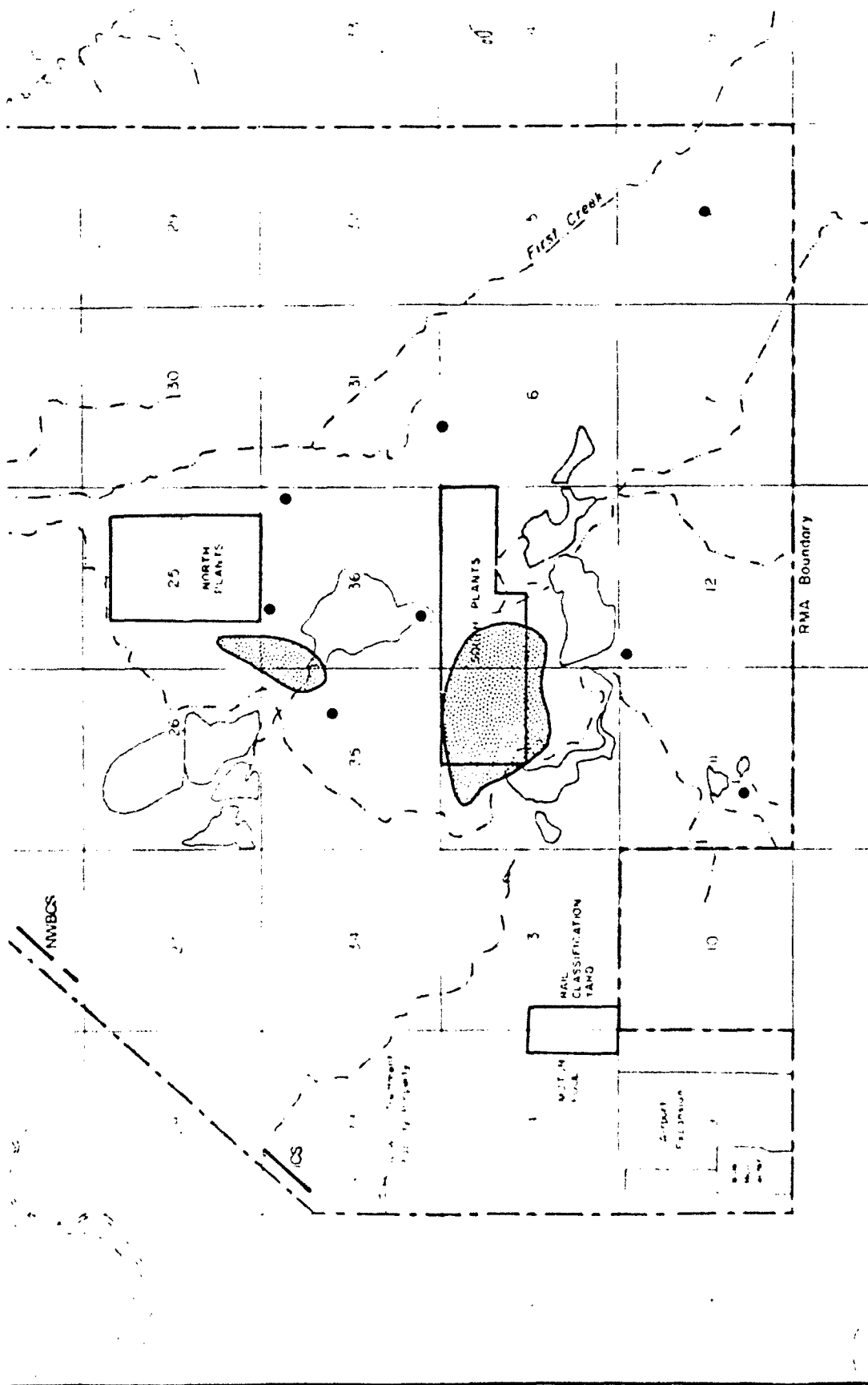
FIGURE 3.11

Areal Extent of Inorganic Analytes
Denver Formation Zone B

Prepared by: R.L. Stollar & Associates Inc.

Source: Compiled from concentration maps in Appendix D and F.





Prepared for:

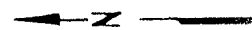
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Aberdeen Proving Ground, Maryland

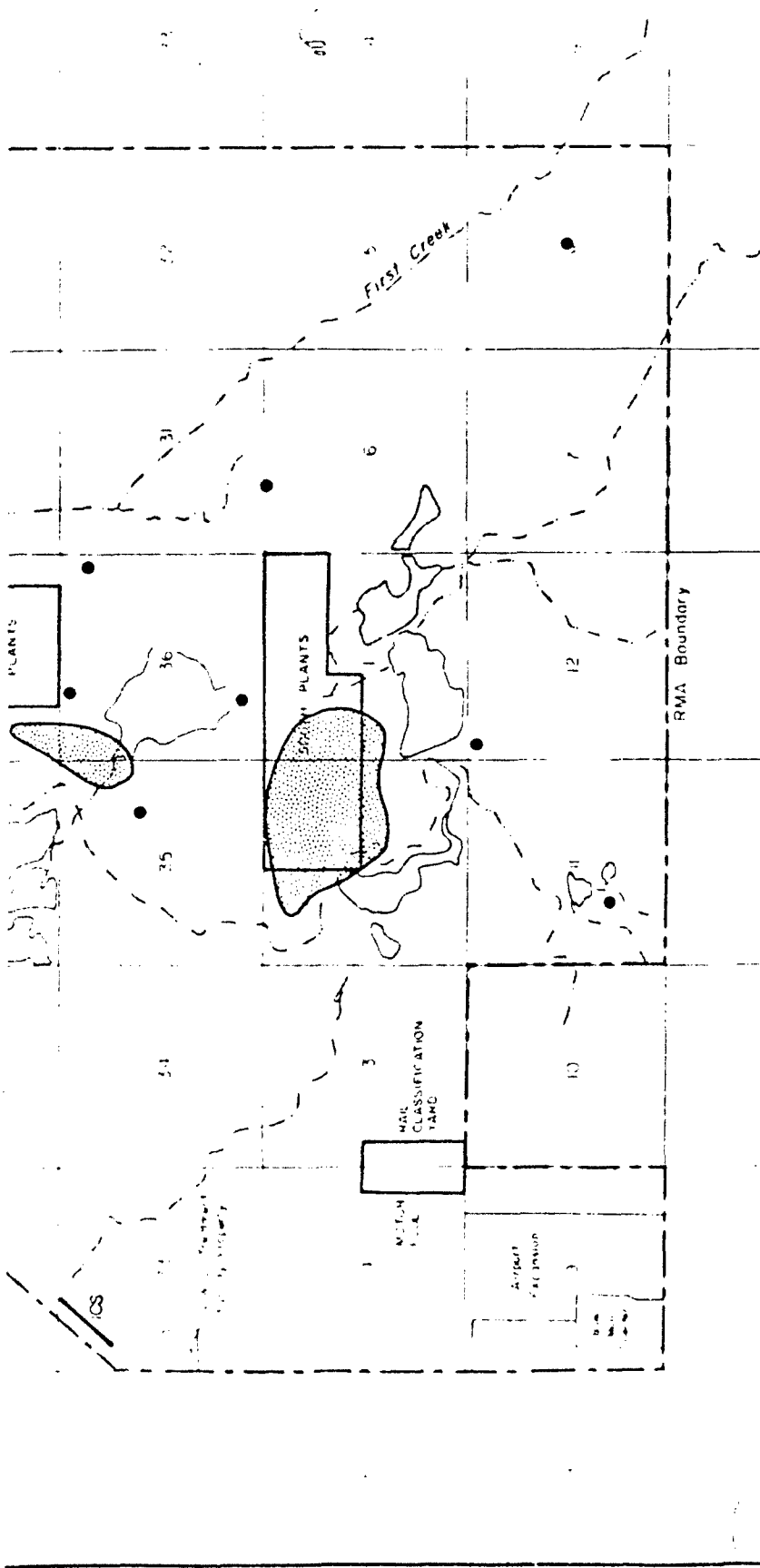
FIGURE 3.12

Explanation

Extent of inorganic analytes

Isolated Detection





Explanation

- Extent of inorganic analytes
- Isolated Detection

Prepared for:

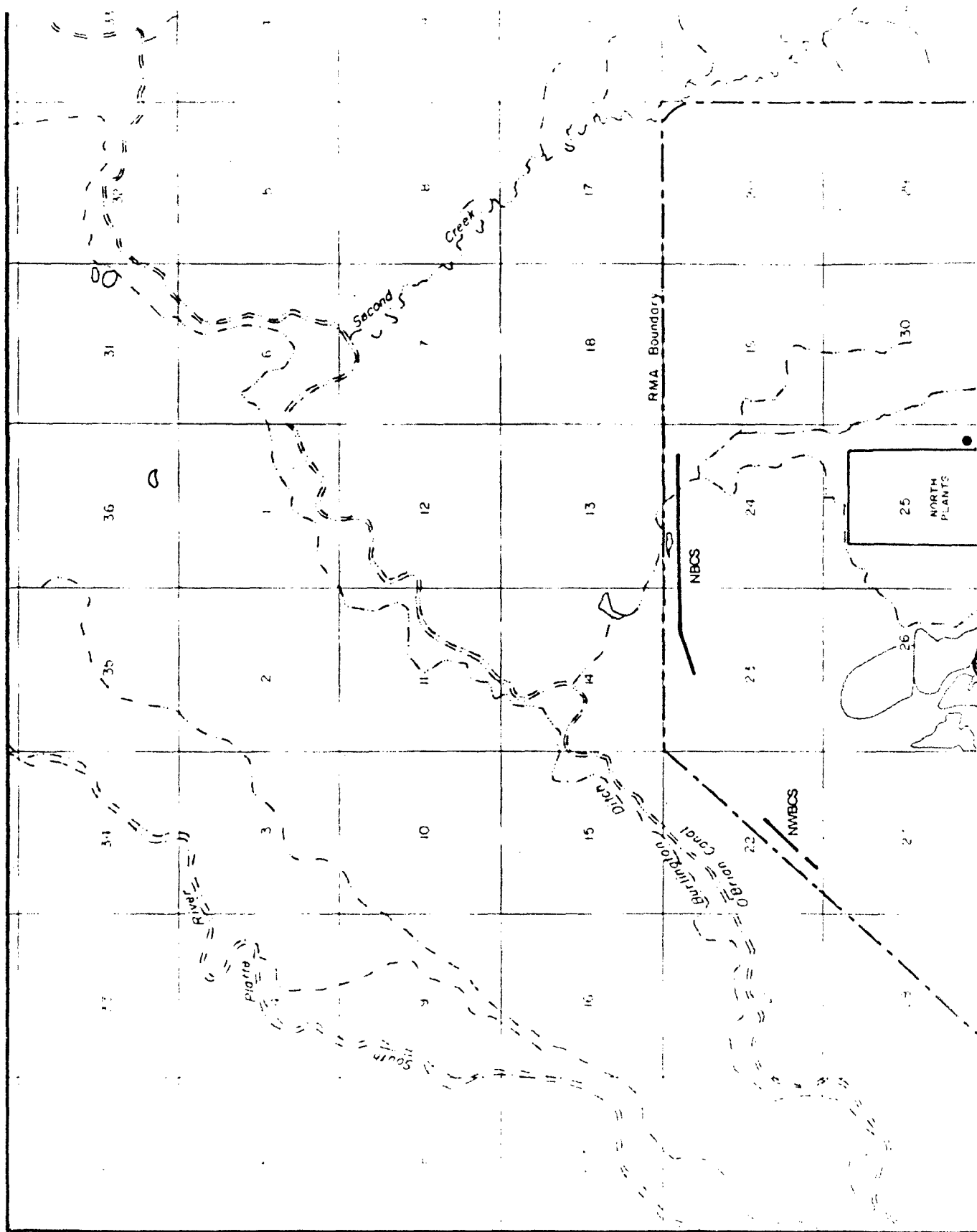
Program Manager's Office for
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Aberdeen Proving Ground, Maryland

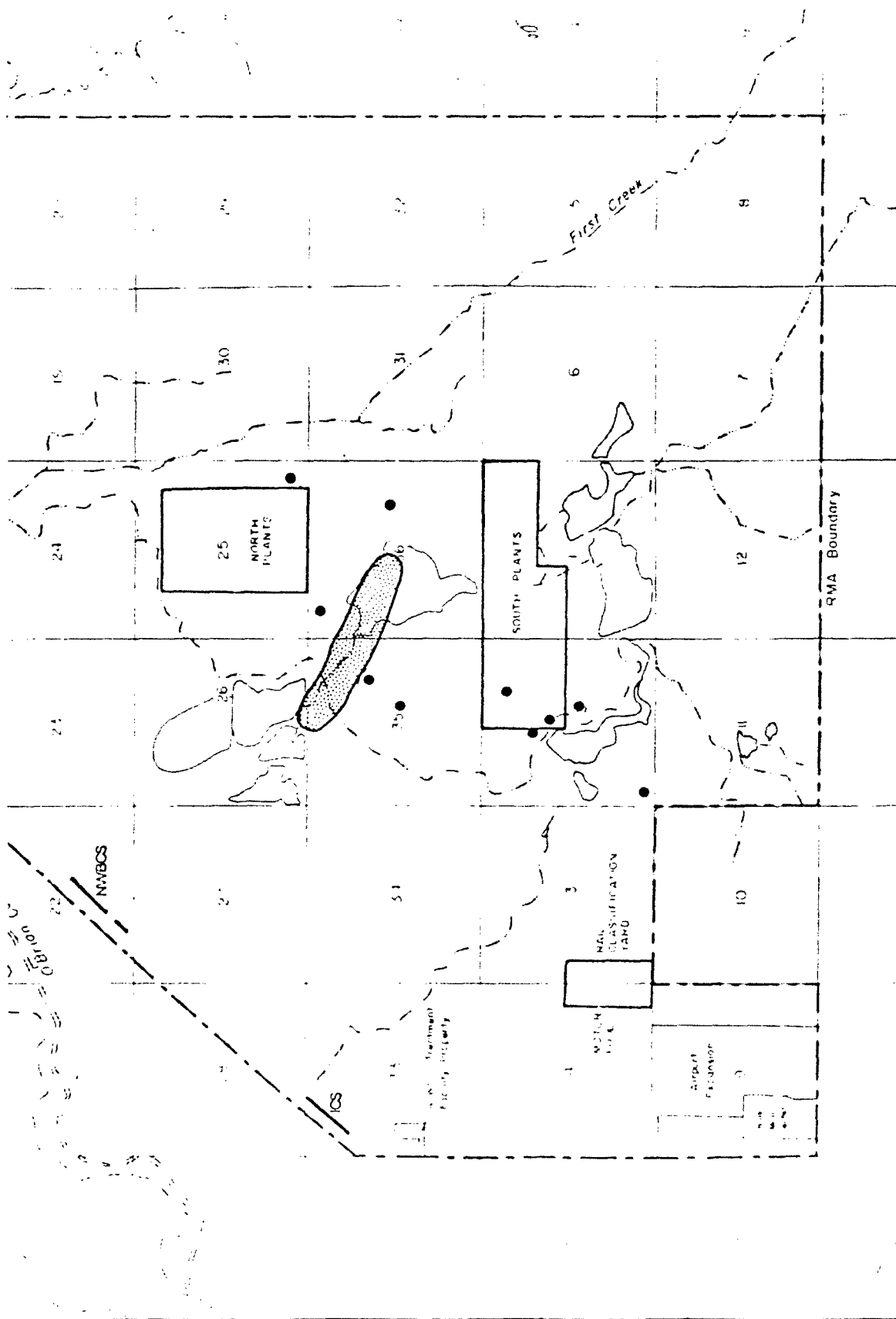
FIGURE 3.12

Areal Extent of Inorganic Analytes
Denver Formation Zone A

Prepared by: R.L. Stollar & Associates Inc.

Source: Compiled from concentration maps in Appendix D and F.





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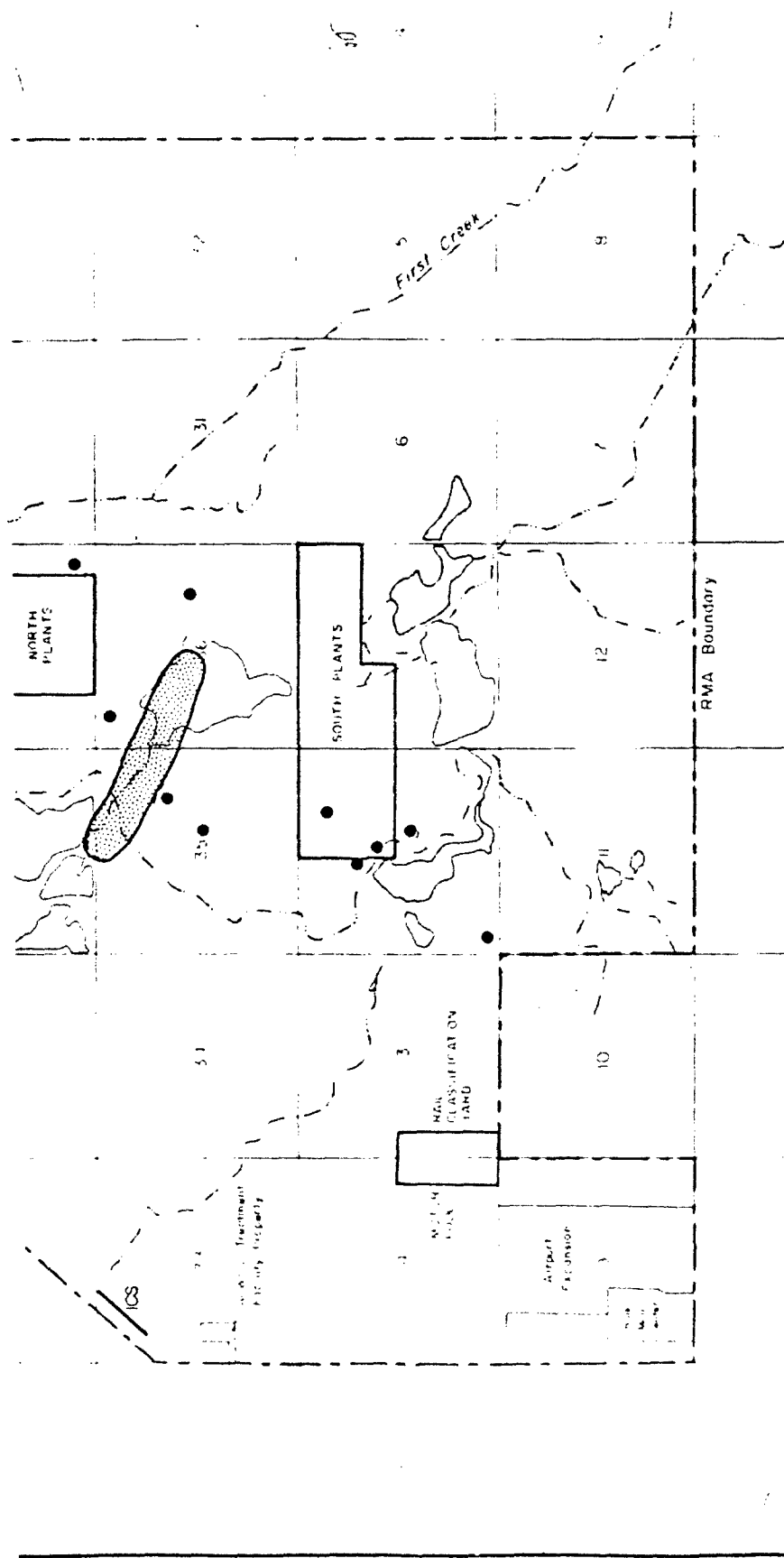
Explanation

Extent of inorganic analytes



Isolated Detection





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FIGURE 3.13

Areal Extent of Inorganic Analytes
Denver Formation Zone 1U

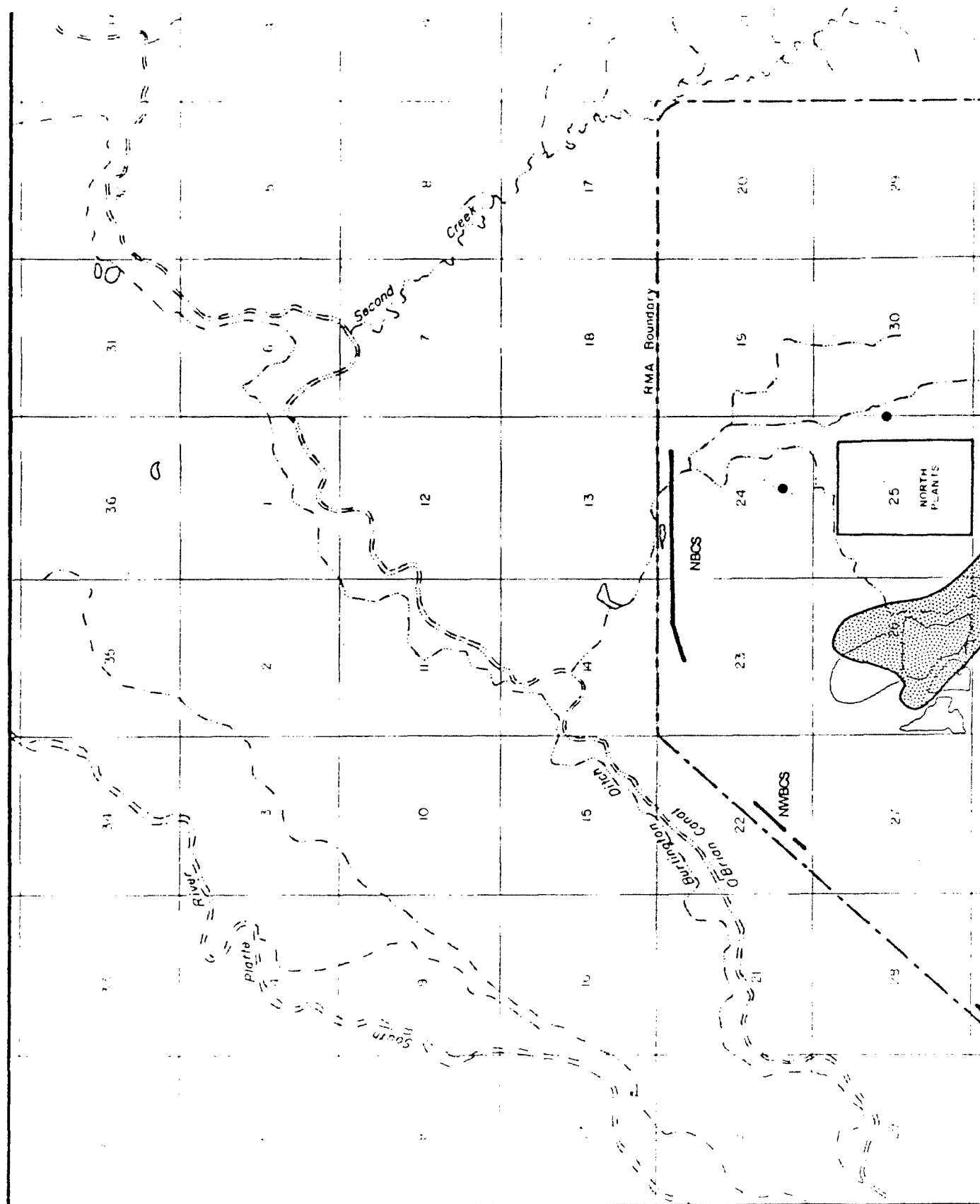
Prepared by: R.L. Stollar & Associates Inc.

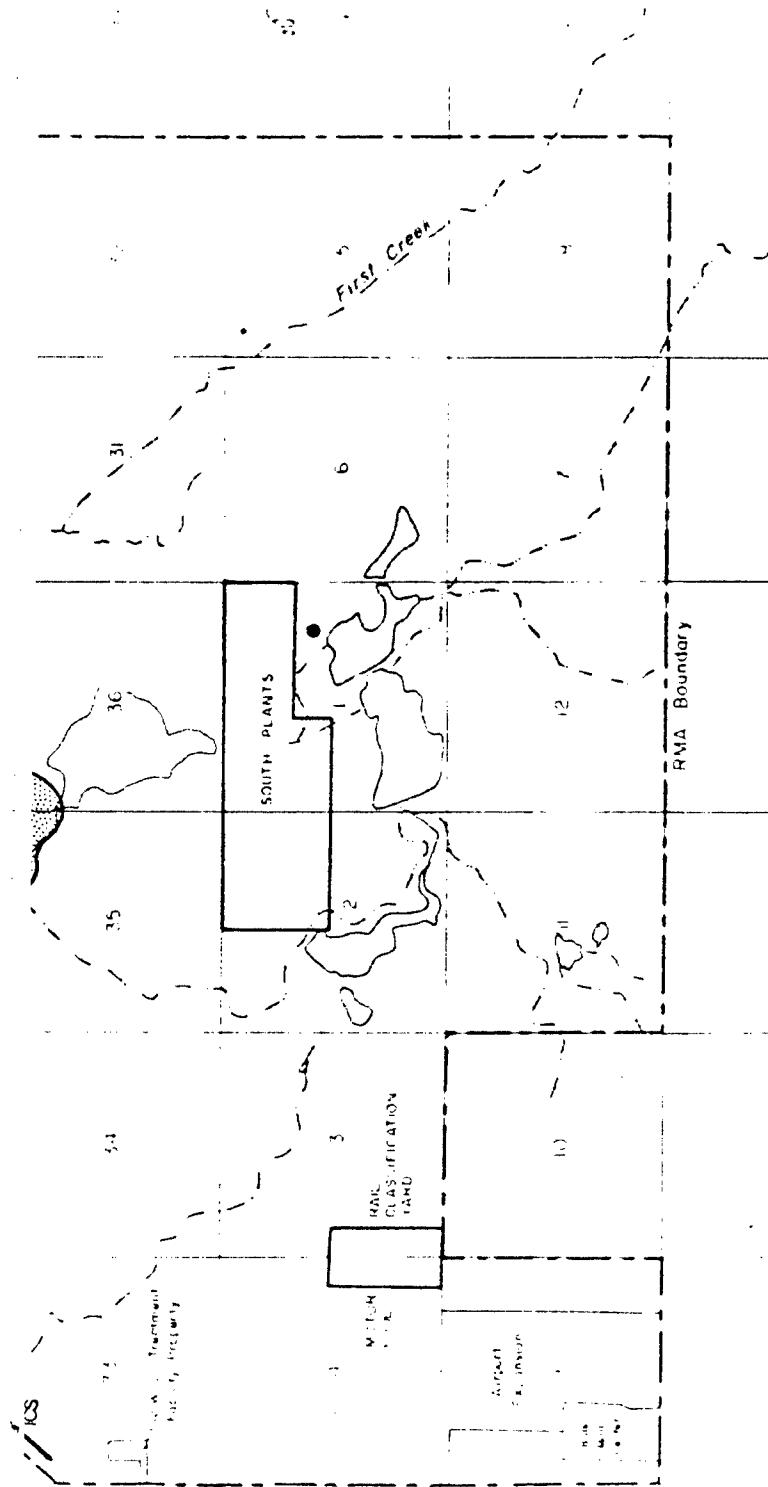
Explanation

Extent of inorganic analytes



Isolated Detection

Source : Compiled from concentration maps in Appendix D and F.





Explanation

-  Extent of inorganic analytes
-  Isolated Detection

Prepared for:

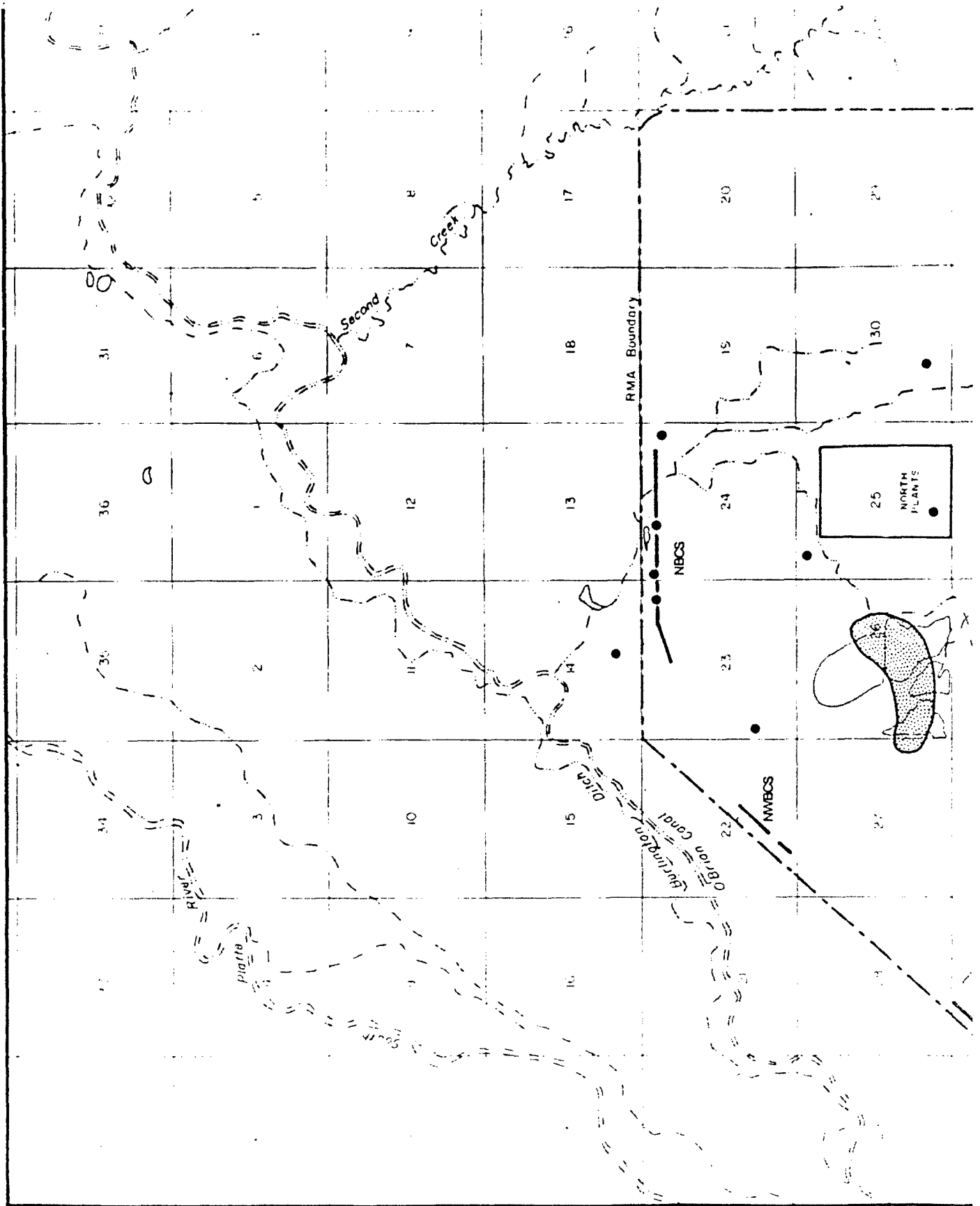
Program Manager's Office for
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Aberdeen Proving Ground, Maryland

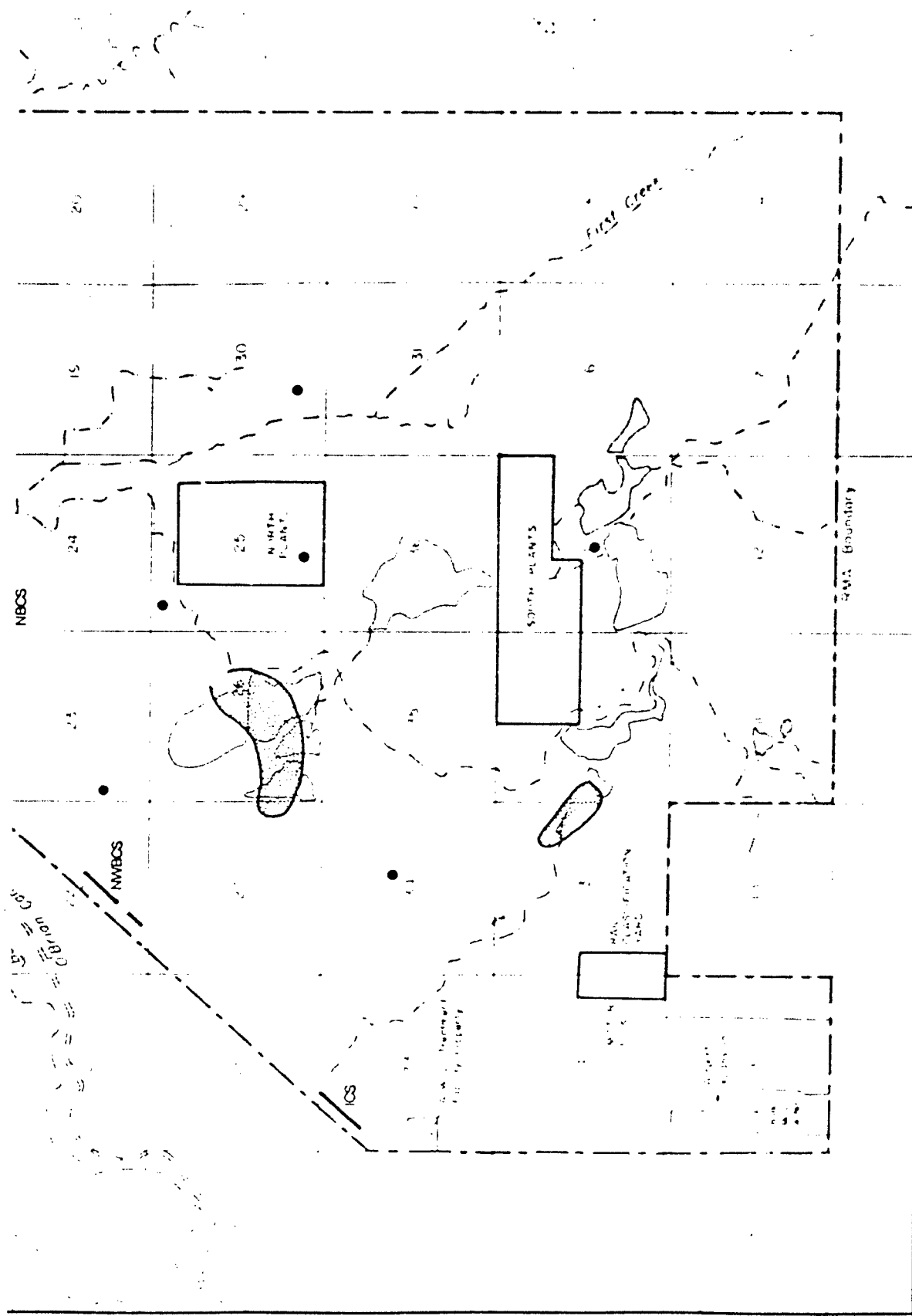
FIGURE 3.14

Areal Extent of Inorganic Analytes
Denver Formation Zone I



Prepared by: R.L. Stollar & Associates Inc.

Source: Compiled from concentration maps in Appendix D and F.



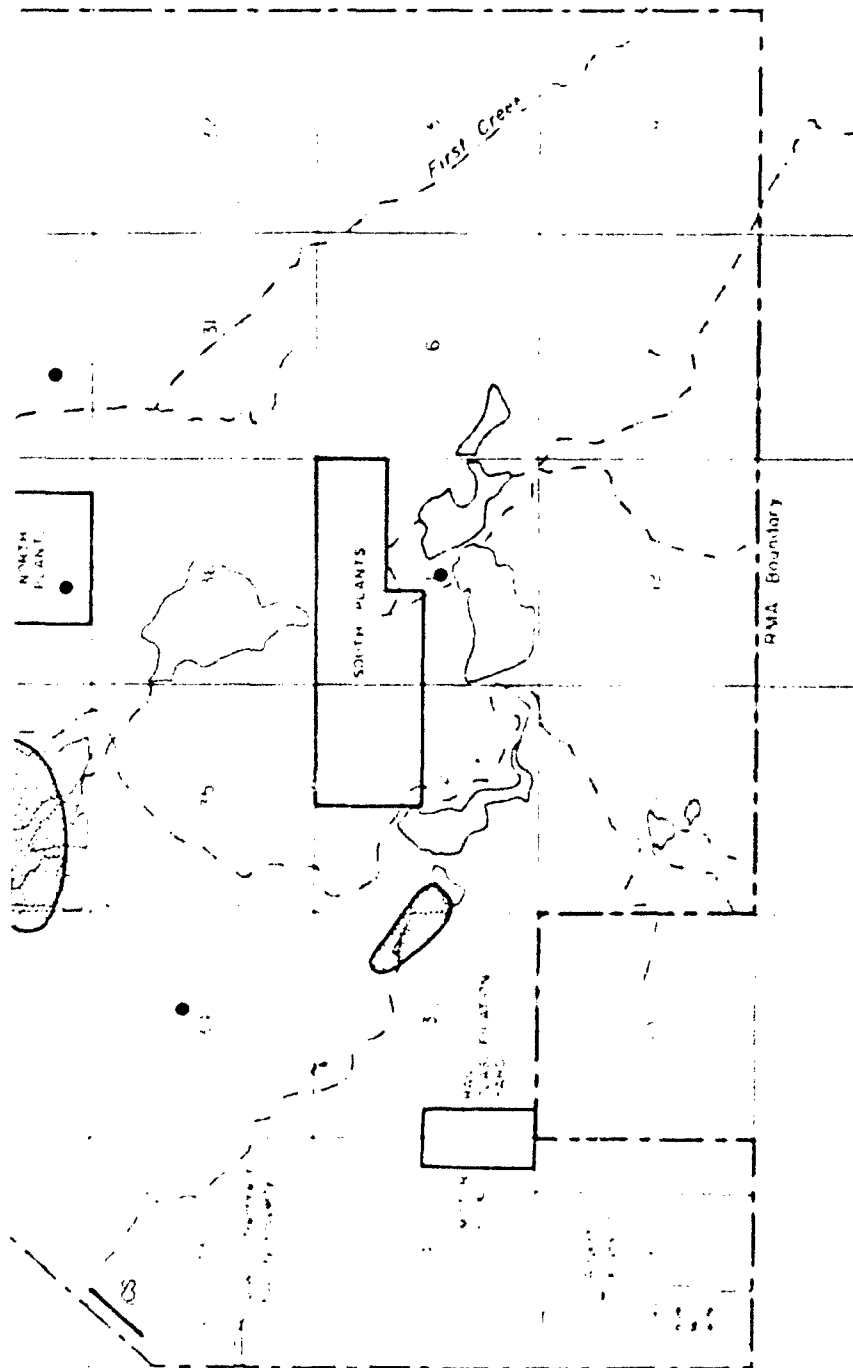


Explanation

-  Extent of inorganic analytes
-  Isolated Detection



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Explanation

Extent of inorganic analytes

Isolated Detection

Prepared for:

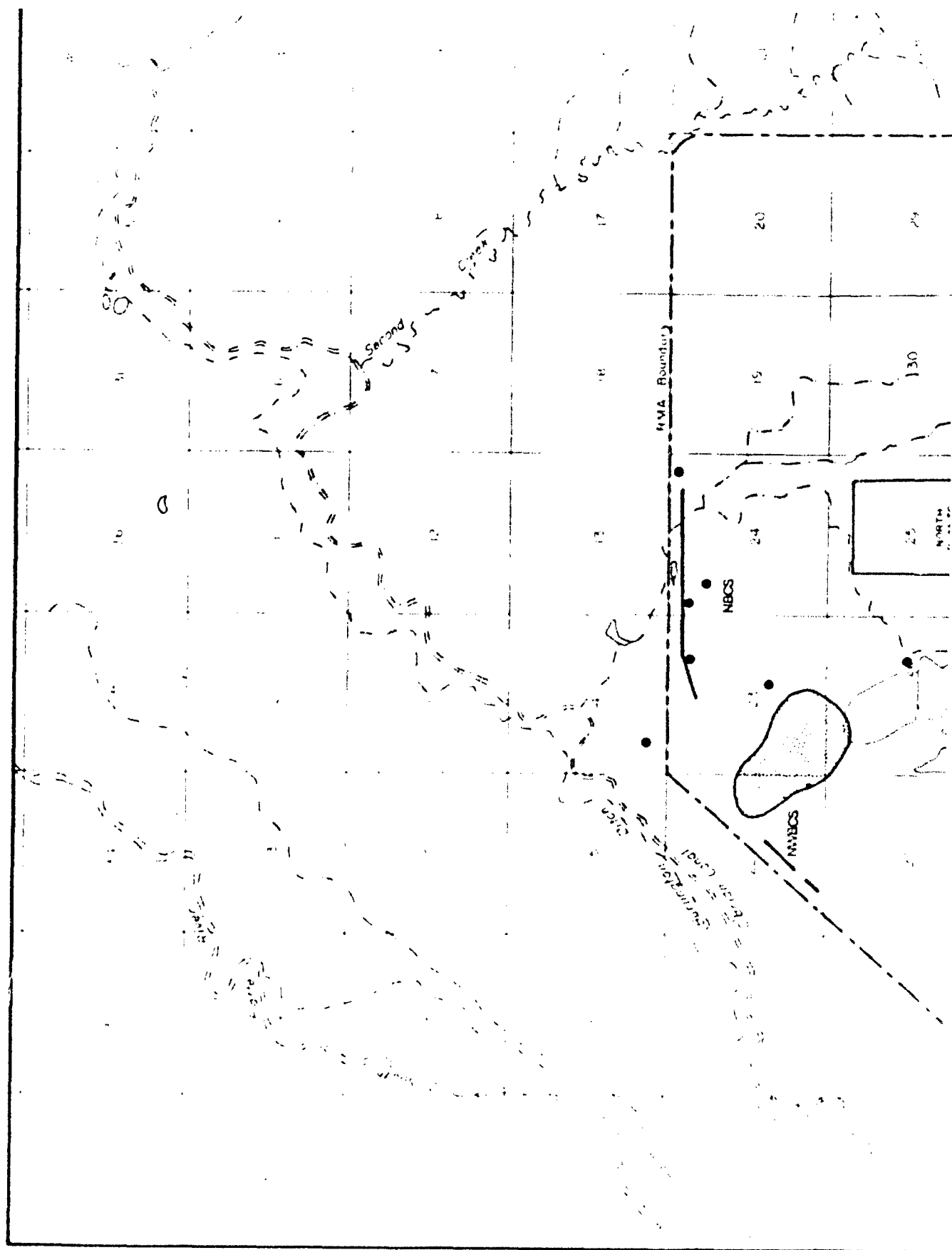
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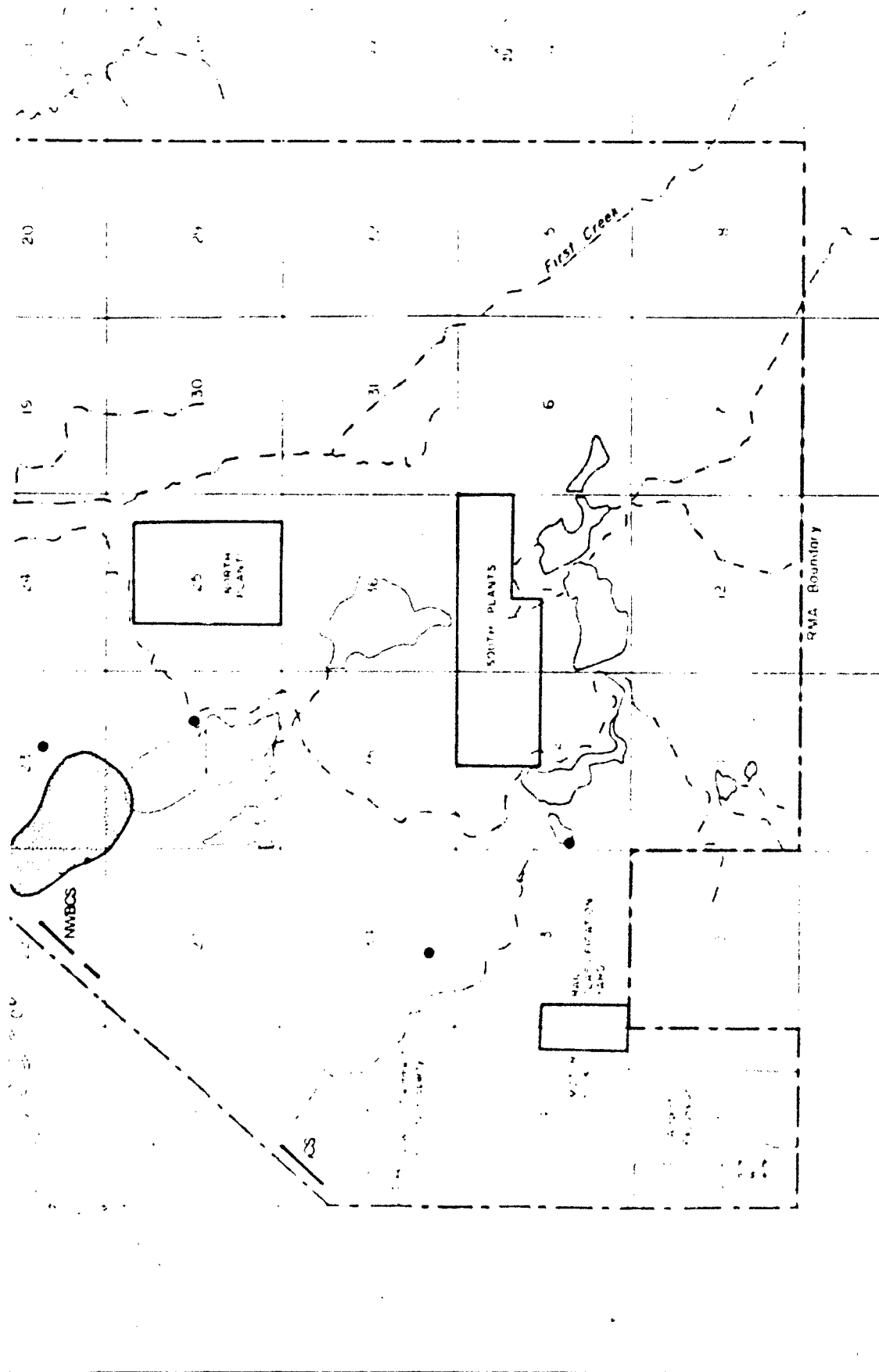
FIGURE 3:15

Areal Extent of Inorganic Analytes
Denver Formation Zone 2

Prepared by: R.L. Stollar & Associates Inc.

Source: Derived from concentration maps in Appendix D and F.

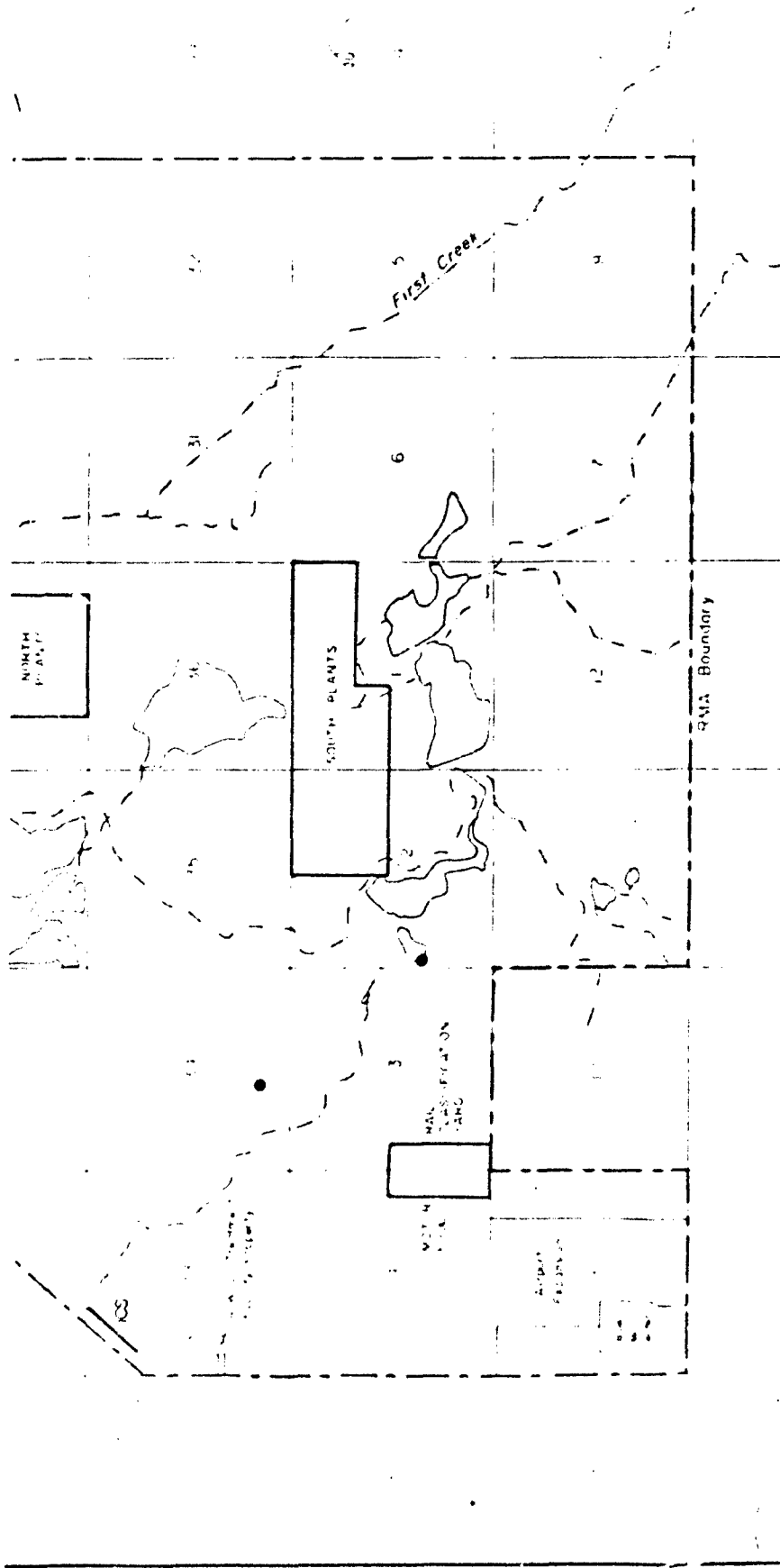




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FIGURE 3.16



Explanation

Extent of inorganic analytes

Isolated Detection

N

0 4000 8000
FEET

Prepared for:

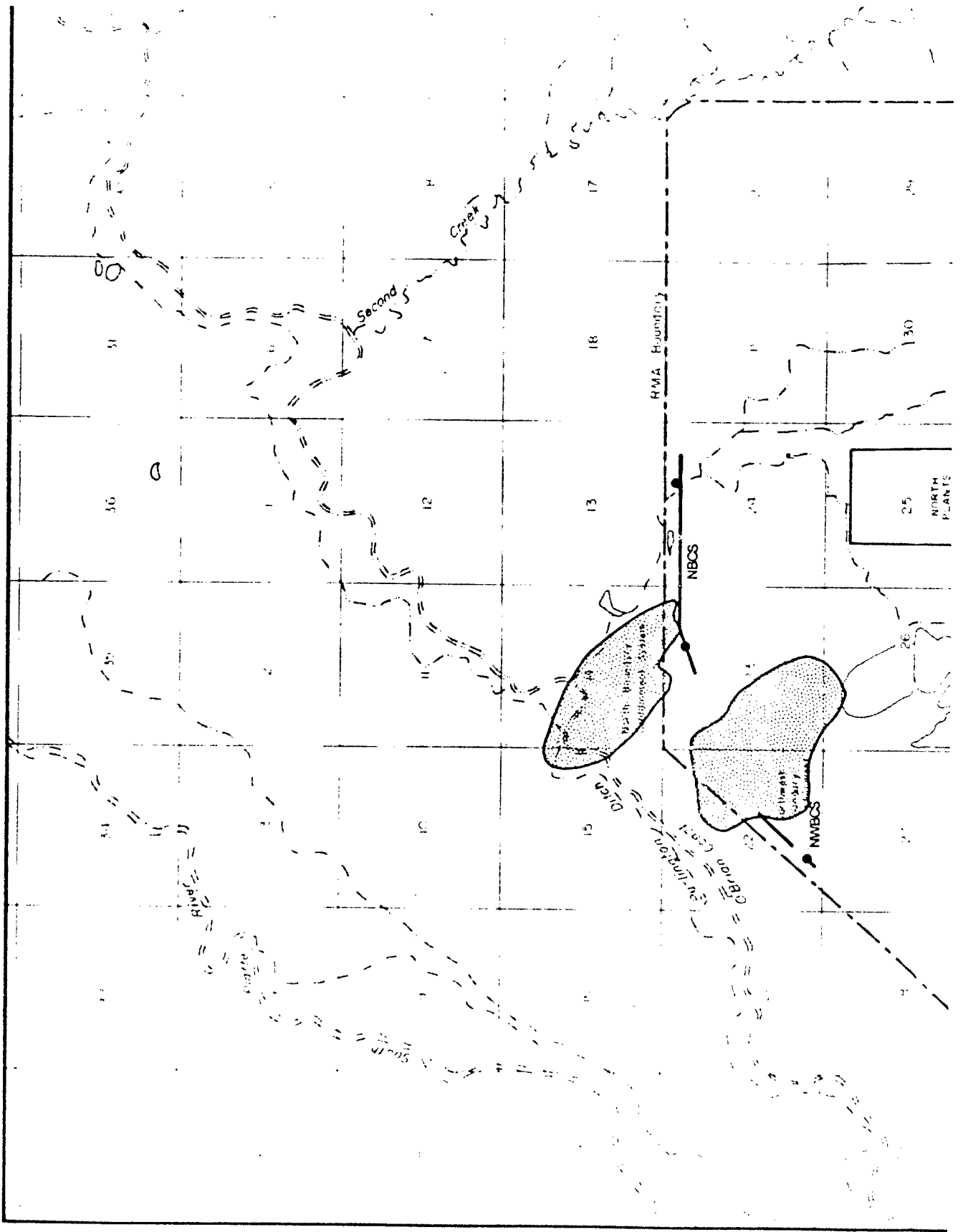
Program Manager's Office for
Rocky Mountain Arsenal Cleanup
Aberdeen Proving Ground, Maryland

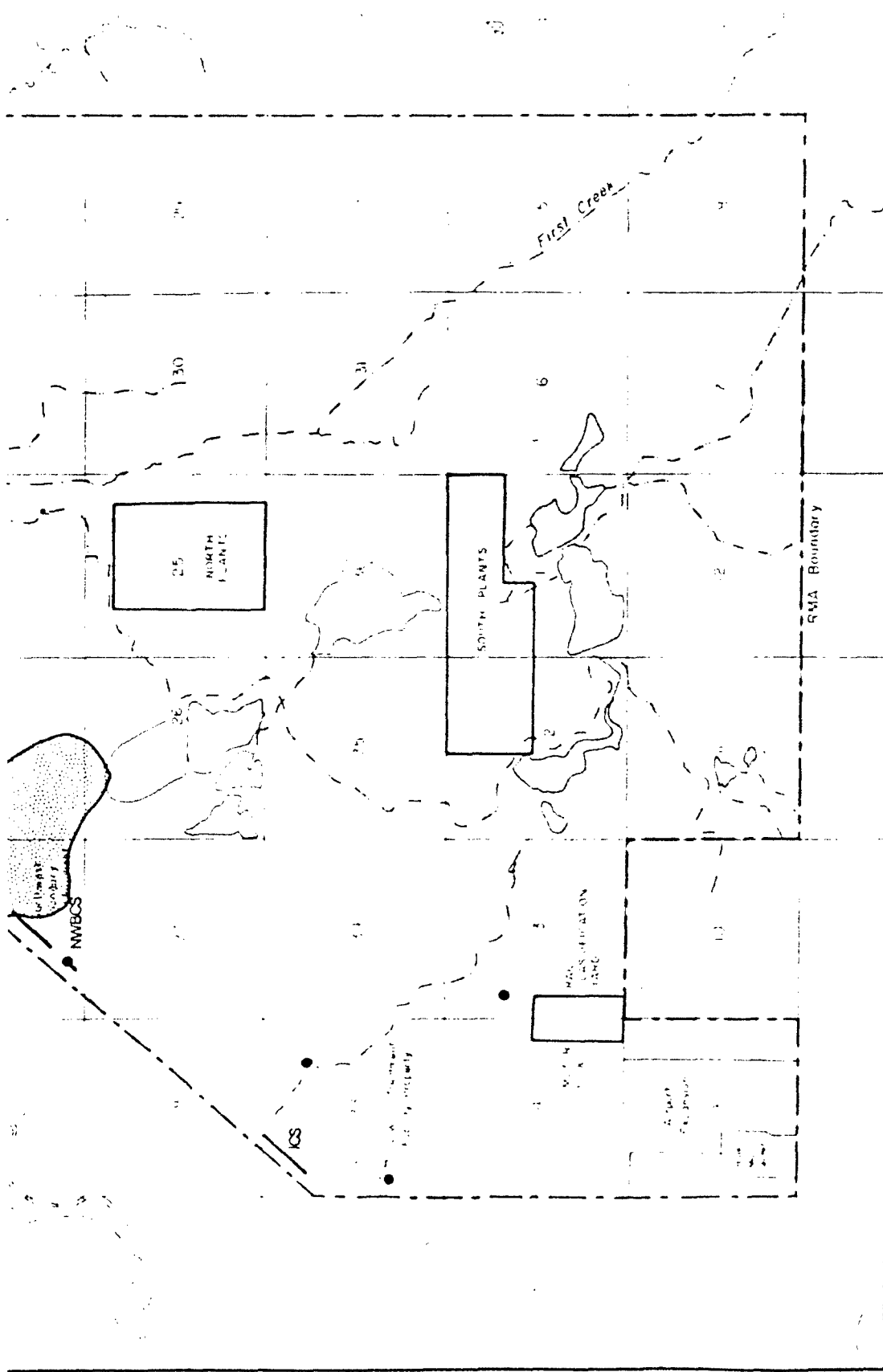
FIGURE 3.16

Areal Extent of Inorganic Analytes
Denver Formation Zone 3

Source: Compiled from concentration maps in Appendix D and F.

Prepared by: R.L. Stollar & Associates Inc.





Explanation

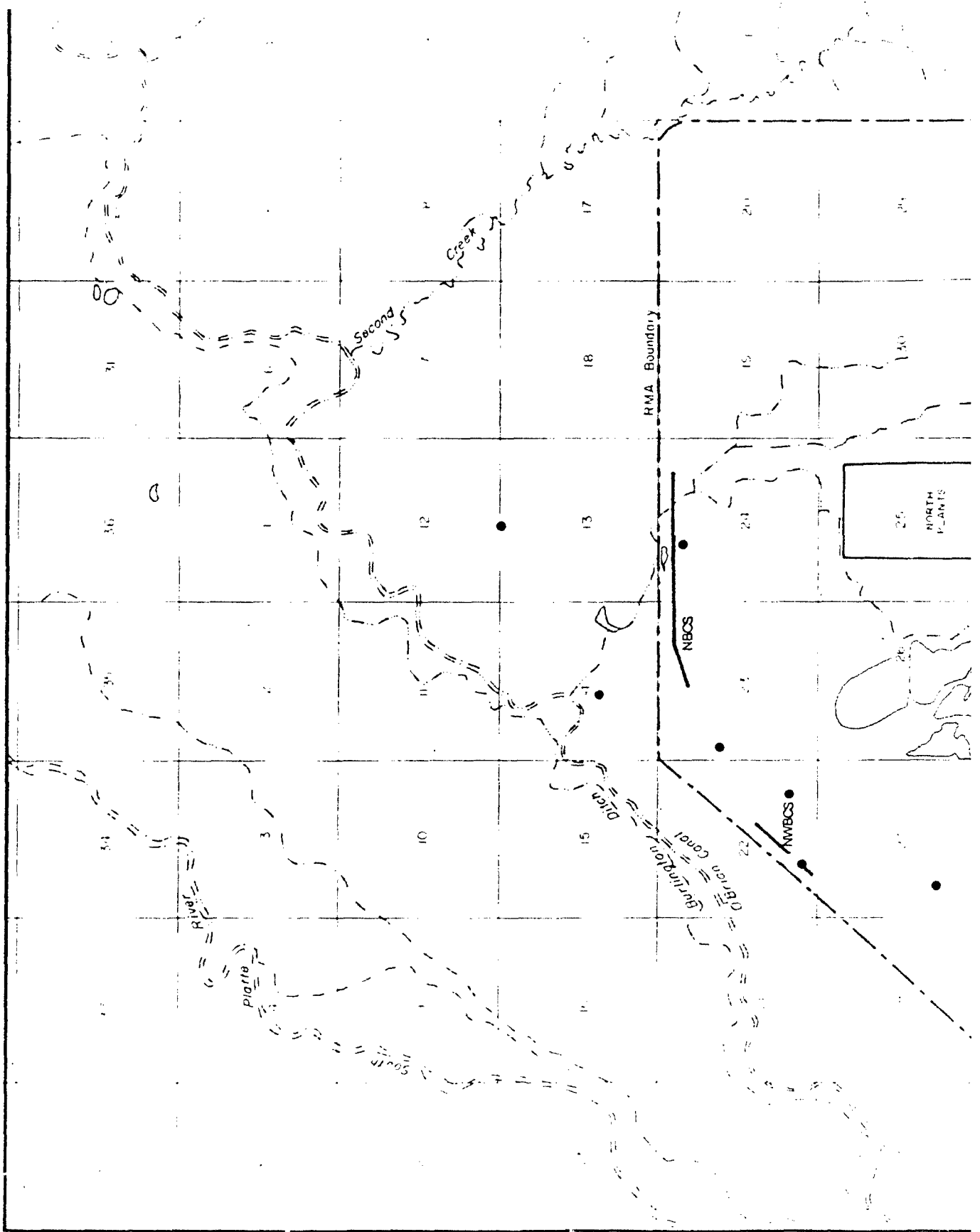
Extent of inorganic analytes

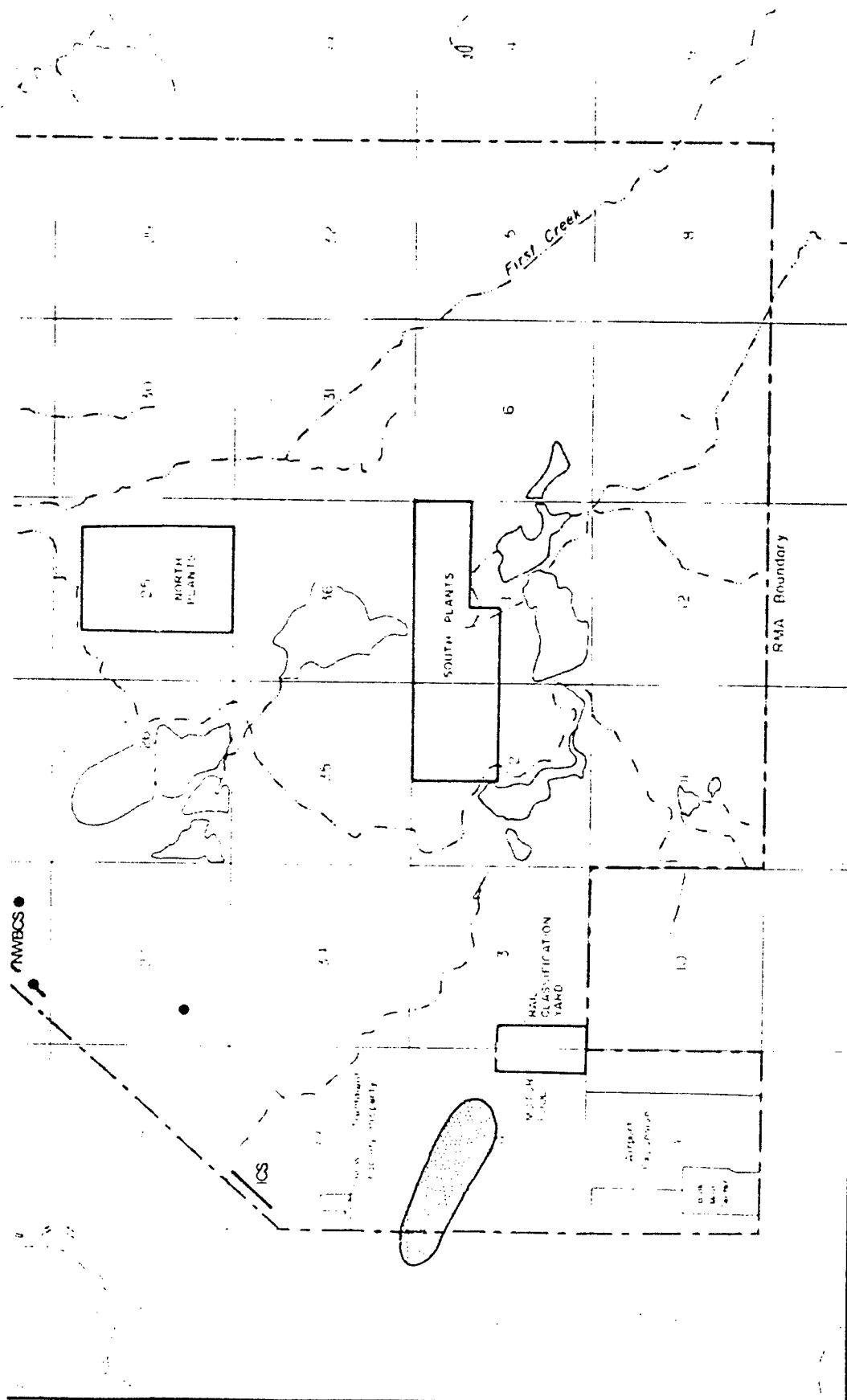
Isolated Detection

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FIGURE 3.17





Explanation

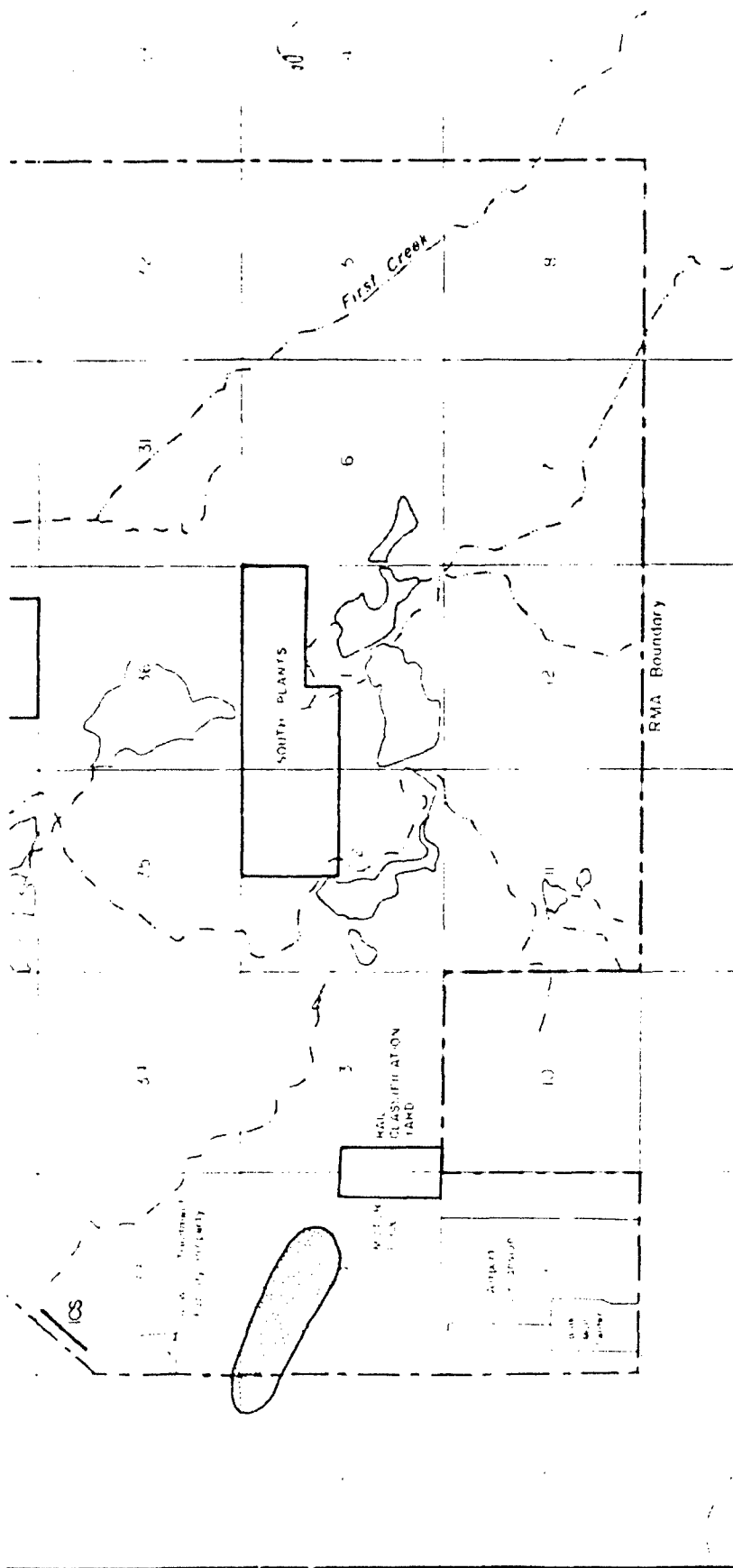
-  Extent of inorganic analytes
-  Isolated Detection

Prepared for:

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FIGURE 3.18

Areal Extent of Inorganic Analytes



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FIGURE 3.18

Areal Extent of Inorganic Analytes
Denver Formation Zone 5

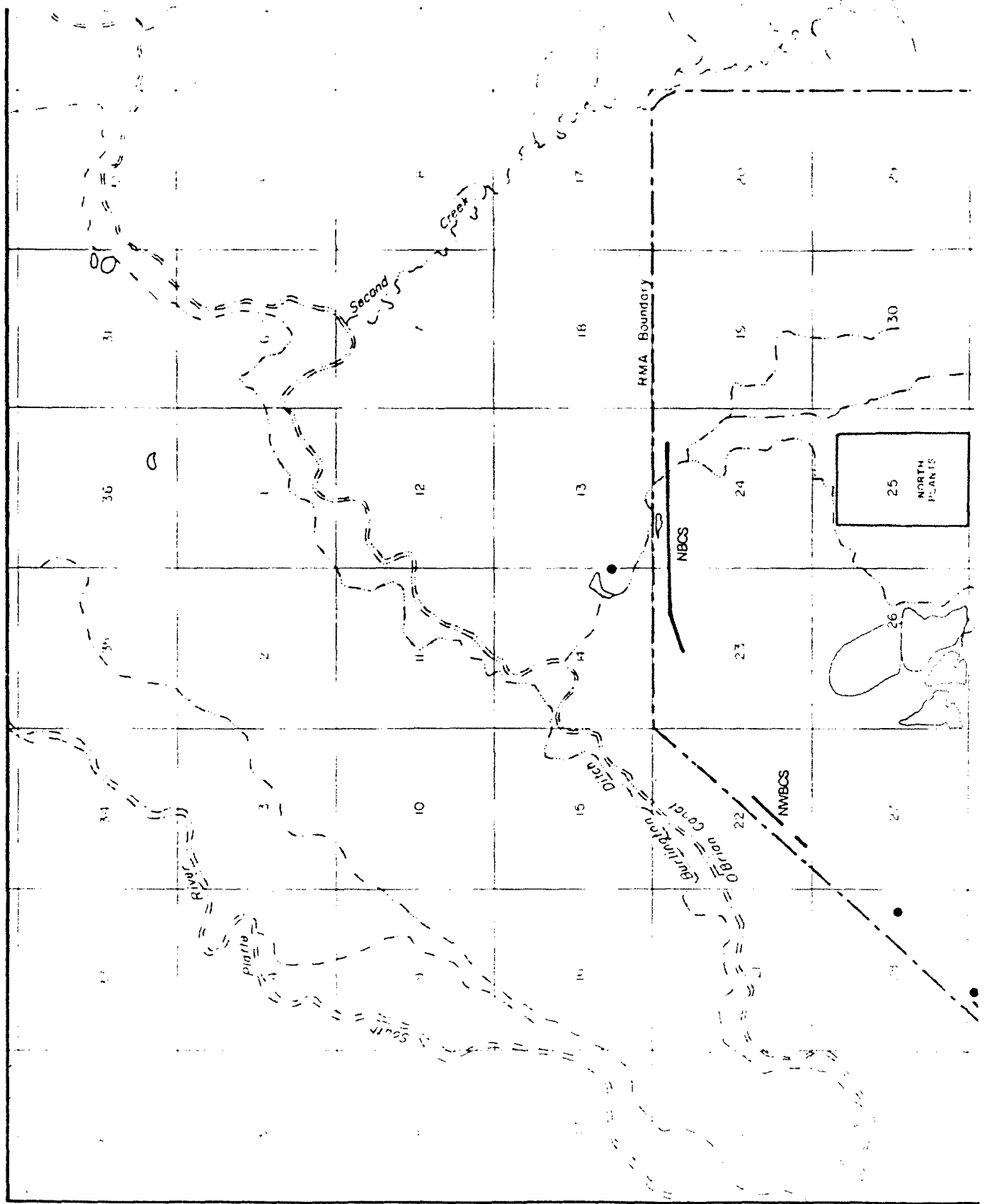
Prepared by: R.L. Stollar & Associates Inc.

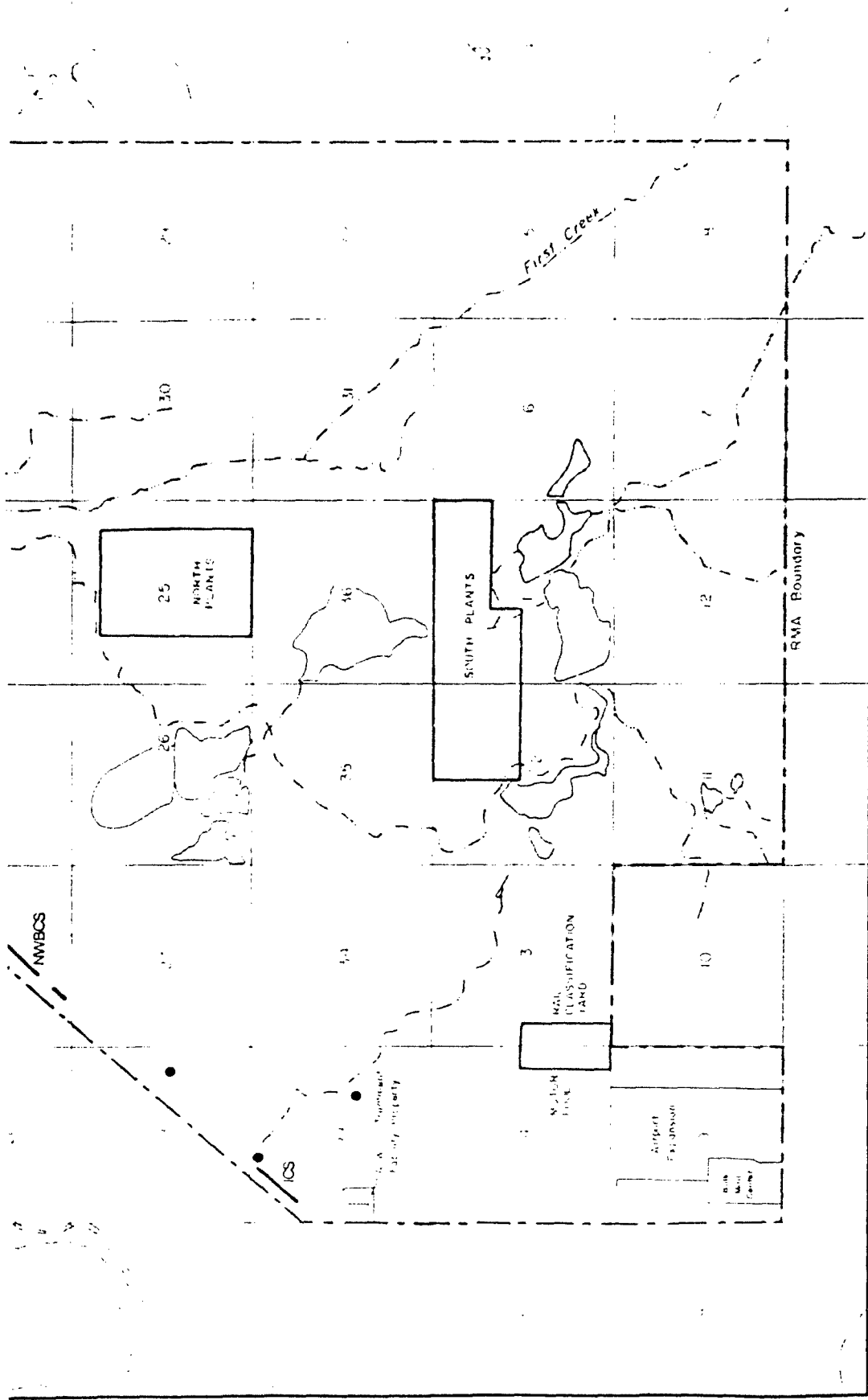
Explanation

Extent of inorganic analytes

Isolated Detection

Source: Compiled from concentration maps in Appendix D and F.





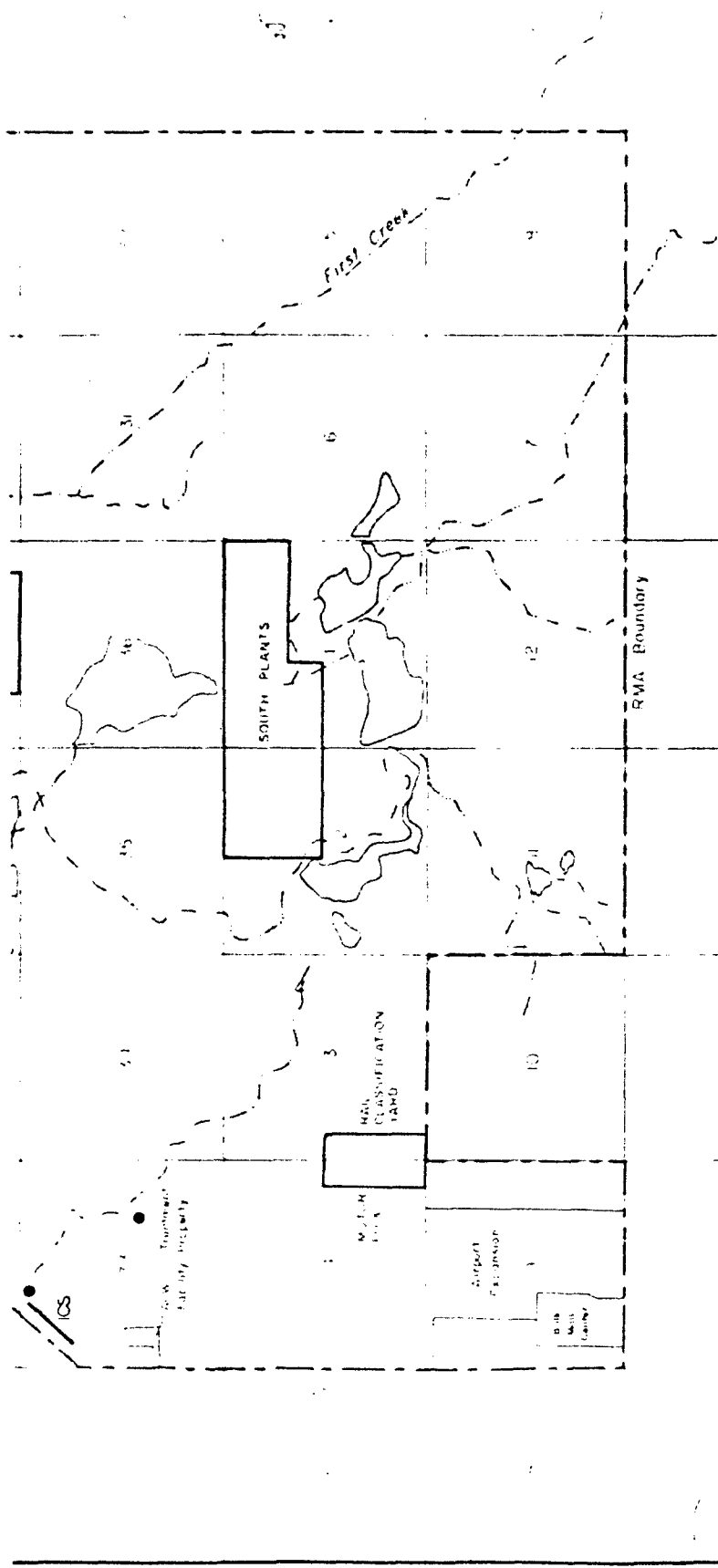
Explanation

- Isolated Detection

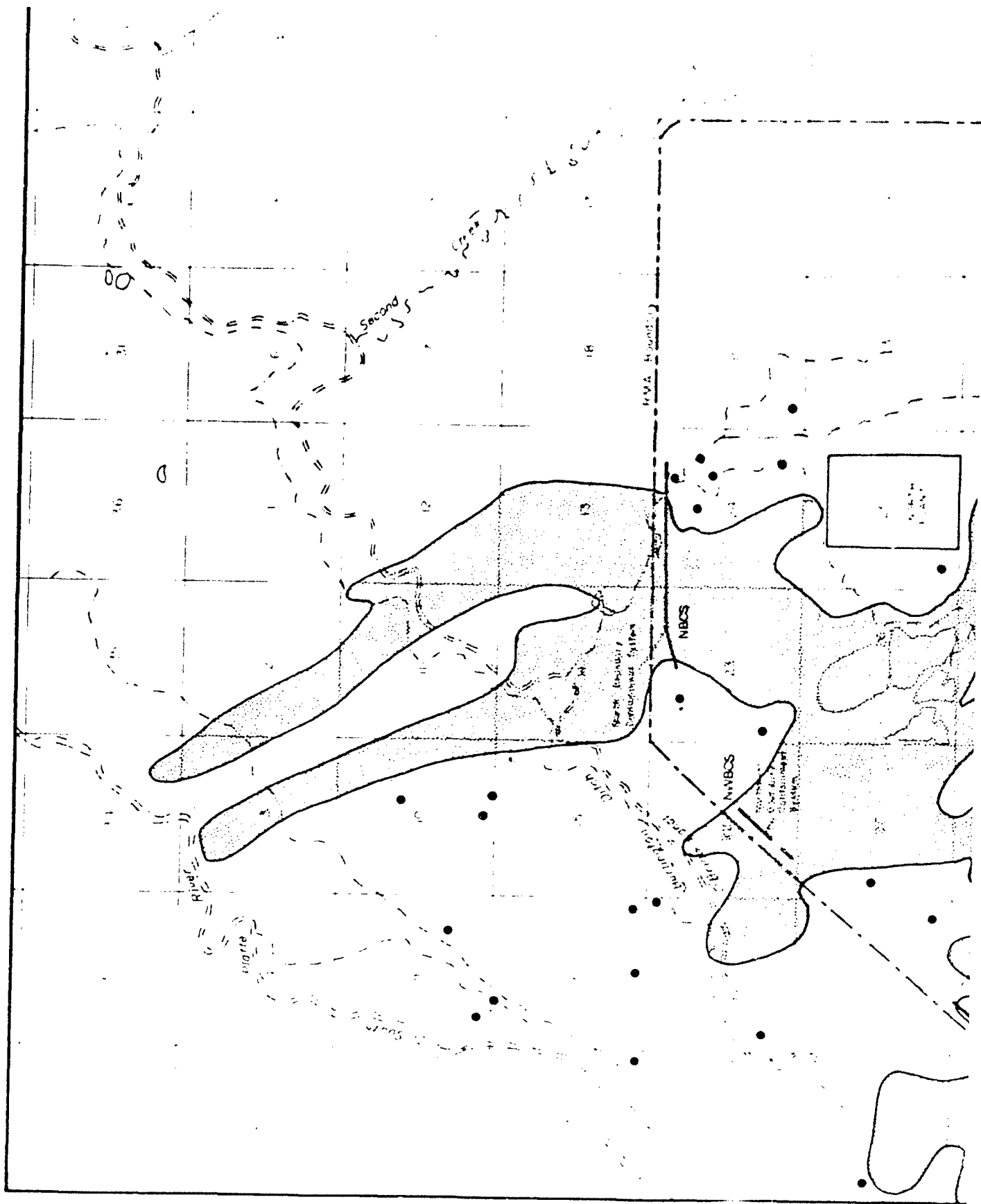
Prepared for:

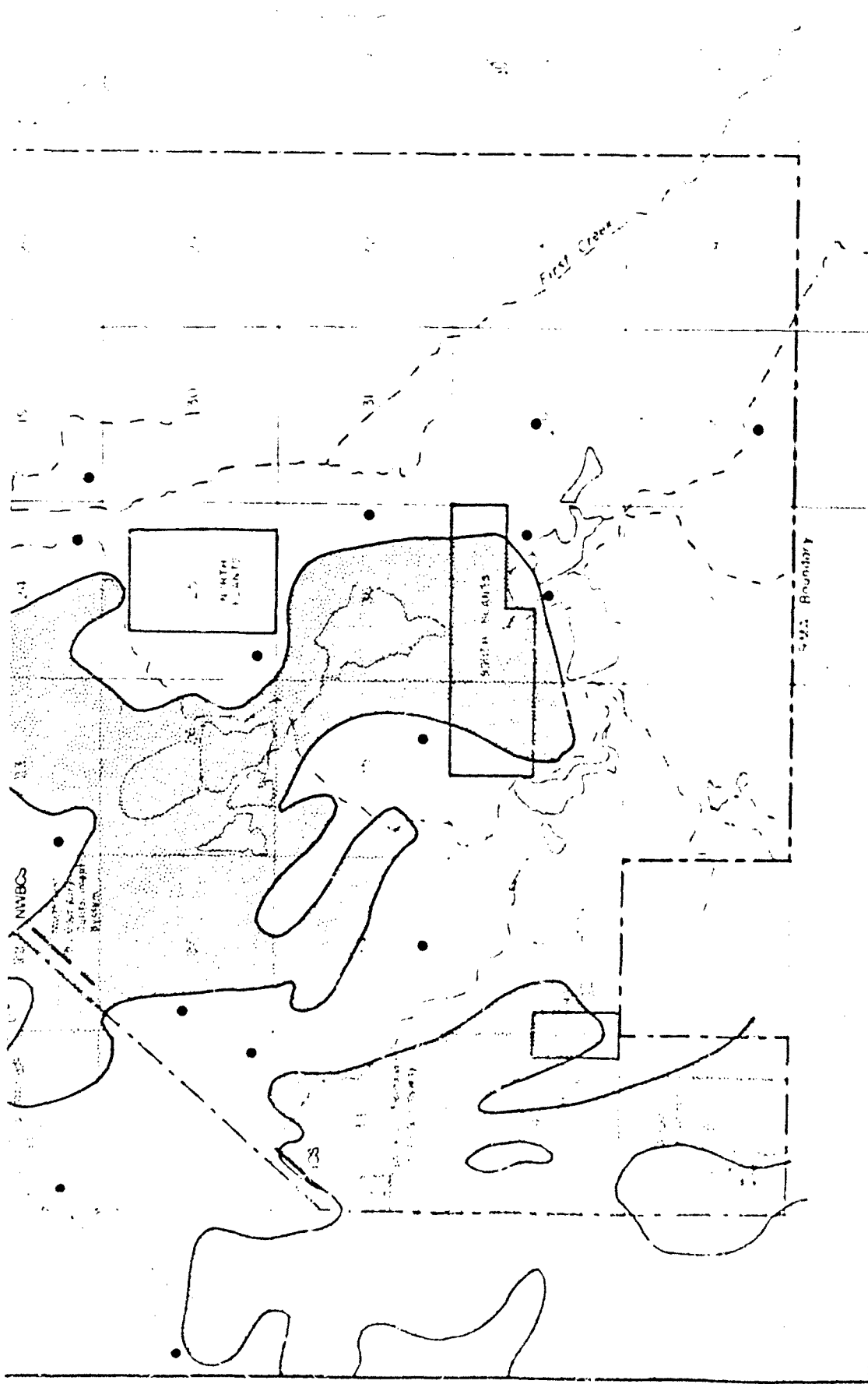
Program Manager's Office for
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FIGURE 3.19



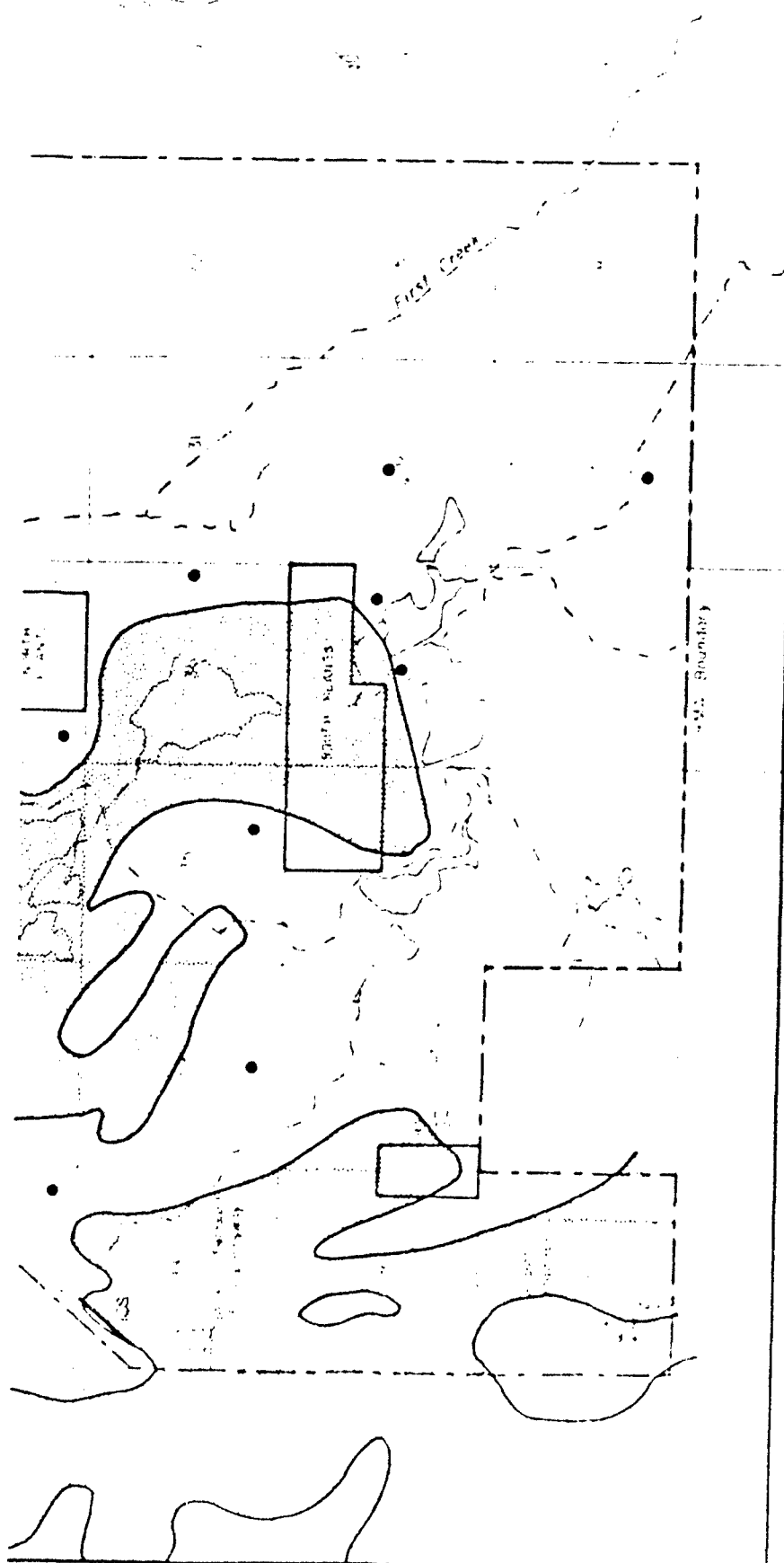
<p>Prepared for:</p> <p>Program Manager's Office for Rocky Mountain Arsenal Cleanup Aberdeen Proving Ground, Maryland</p>	<p><u>Explanation</u></p> <ul style="list-style-type: none"> ● Isolated Detection
<p>FIGURE 3.19</p> <p>Areal Extent of Inorganic Analytes Denver Formation Zones 6 and 7</p> <p>Prepared by: R L. Stollar & Associates Inc.</p>	<p>Source : Compiled from concentration maps in Appendix D and F.</p>





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FIGURE 3.20



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Aberdeen Proving Ground, Maryland

FIGURE 3.20

Areal Extent of Organic Analytes in the
Unconfined Flow System

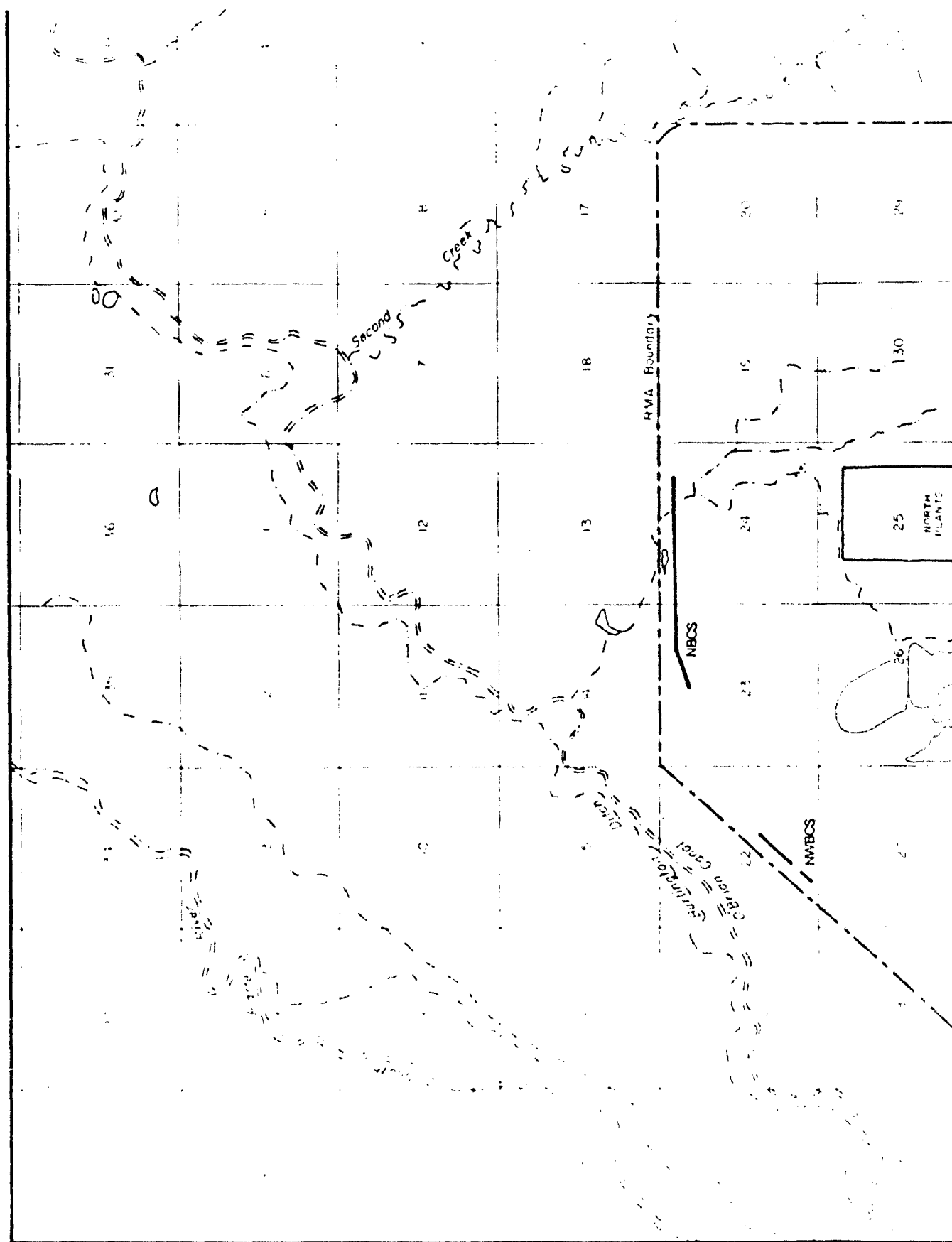
Prepared by: R.L. Stollar & Associates Inc.

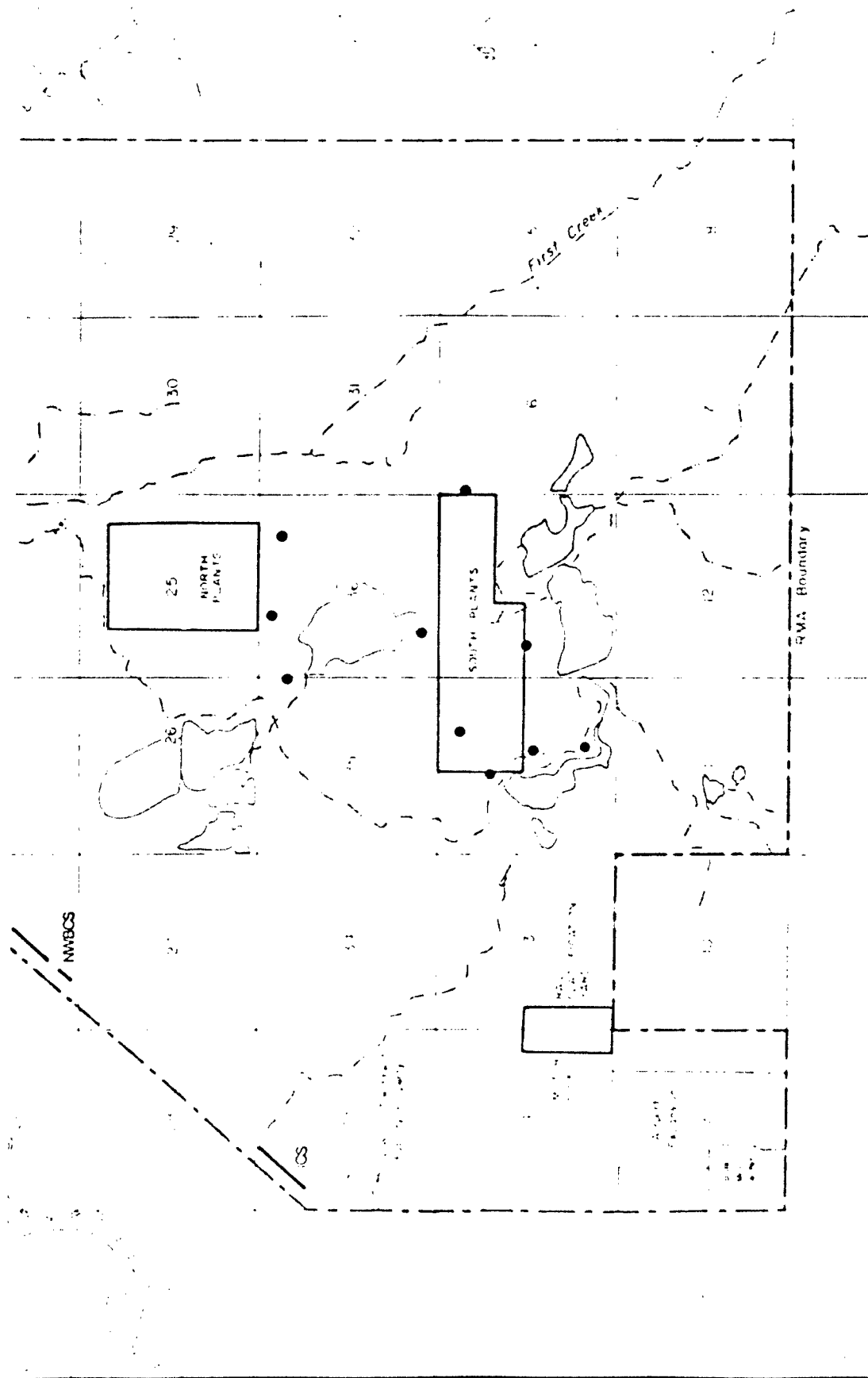
Explanation

Extent of organic analytes

Isolated Detection

Source: Compiled from concentration maps in Appendix D and E.





Explanation:

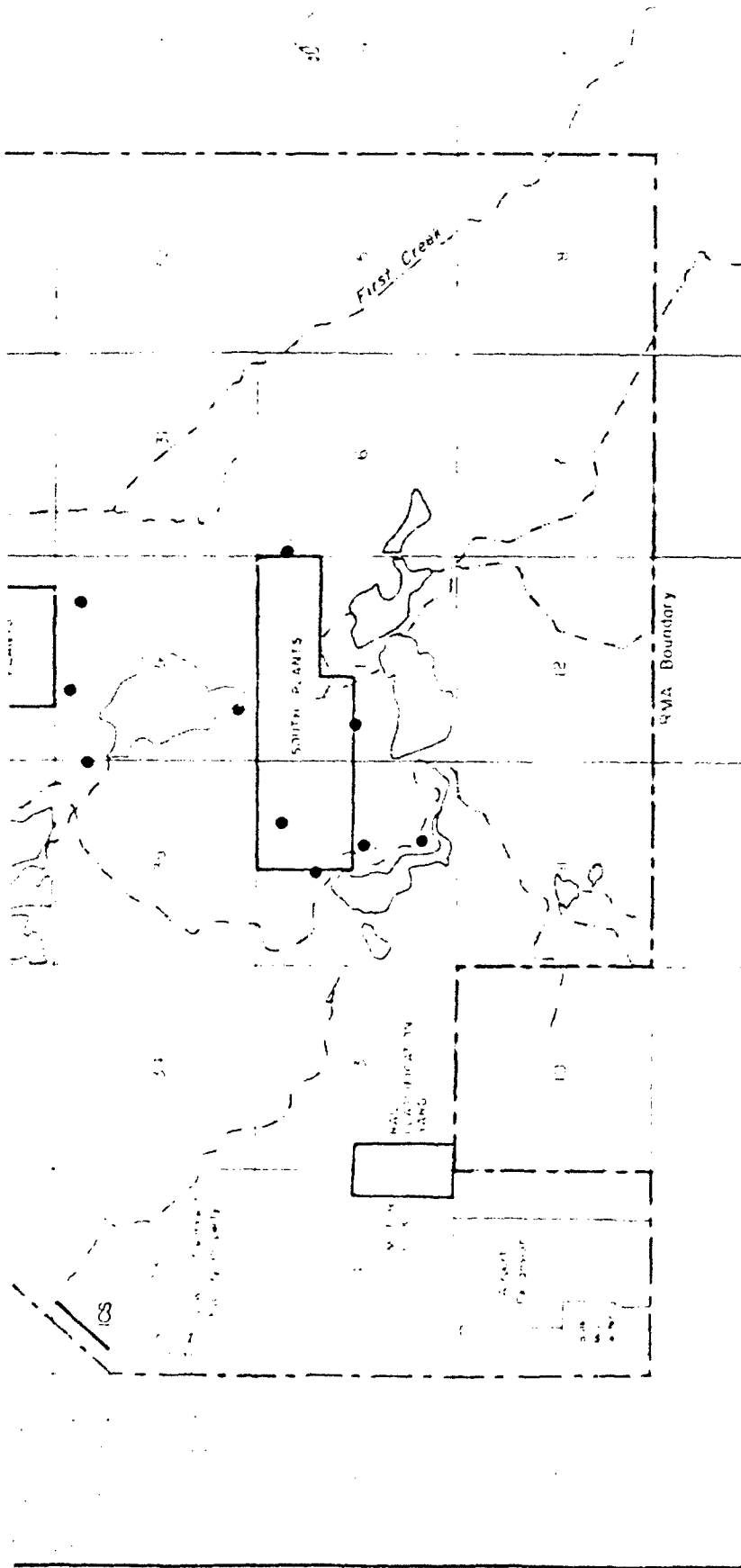
- Isolated Detection

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Aberdeen Proving Ground, Maryland

FIGURE 3.21

Area Extent of Organic Analytes



Explanation

- Isolated Detection

Prepared for:

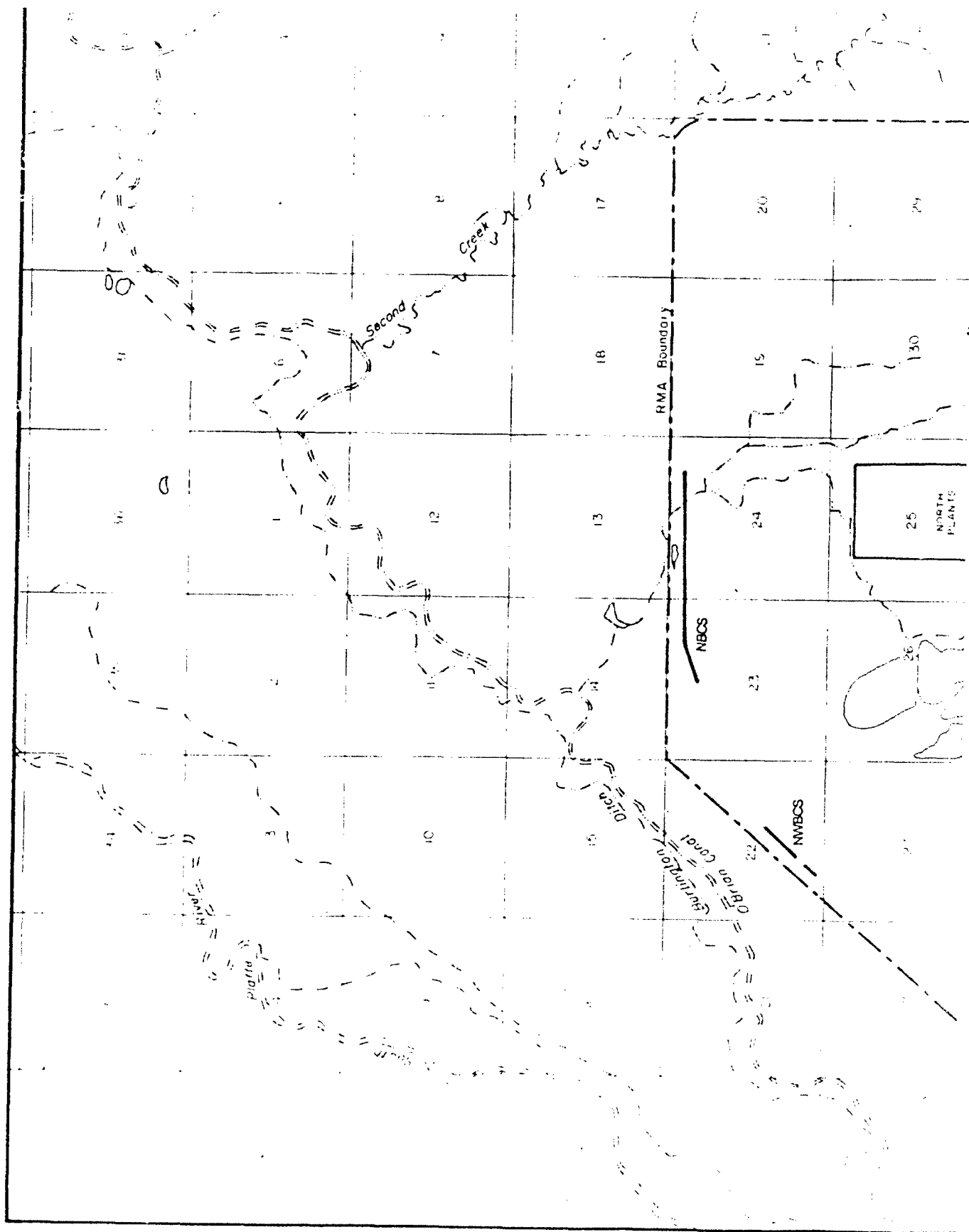
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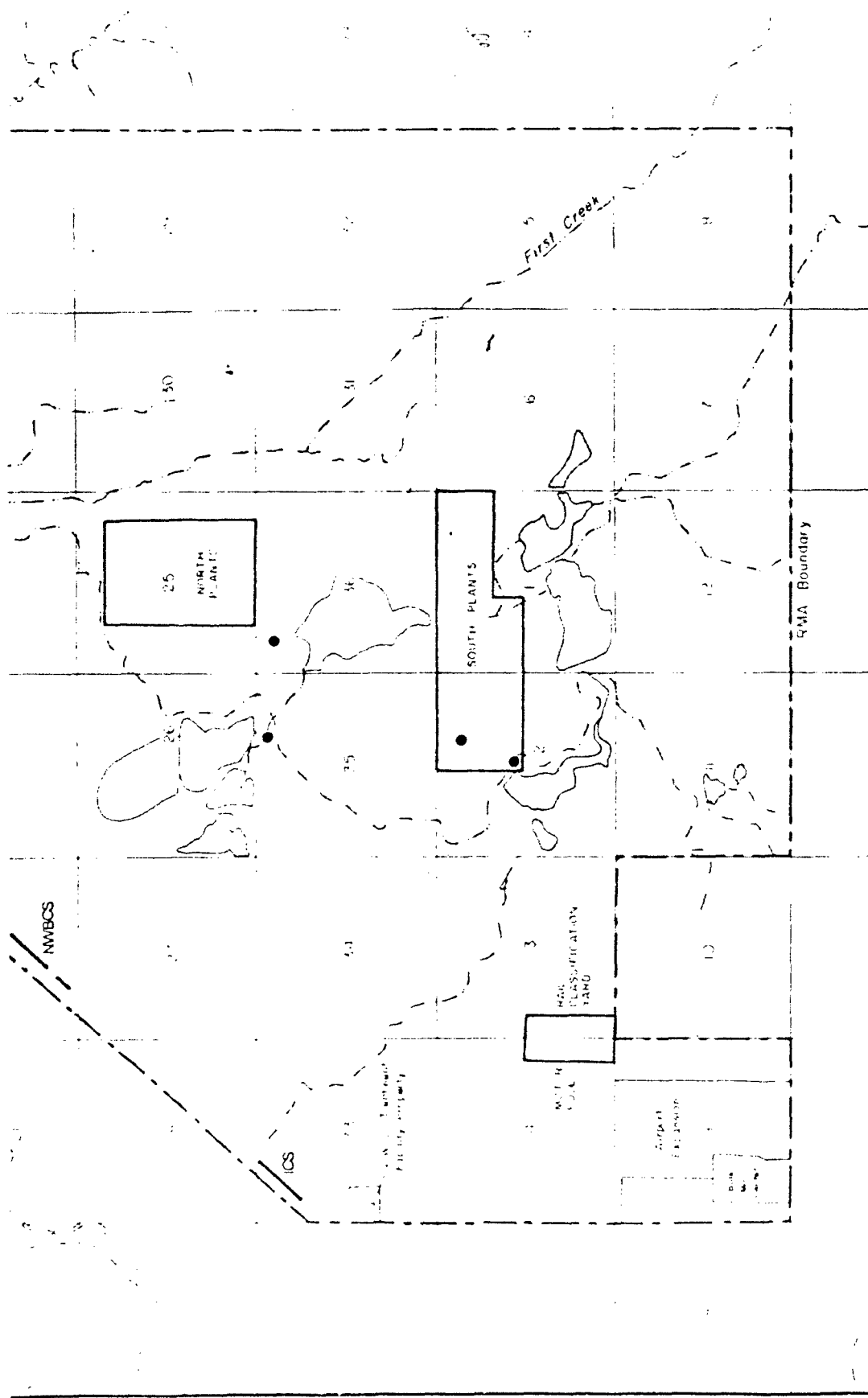
FIGURE 3.21

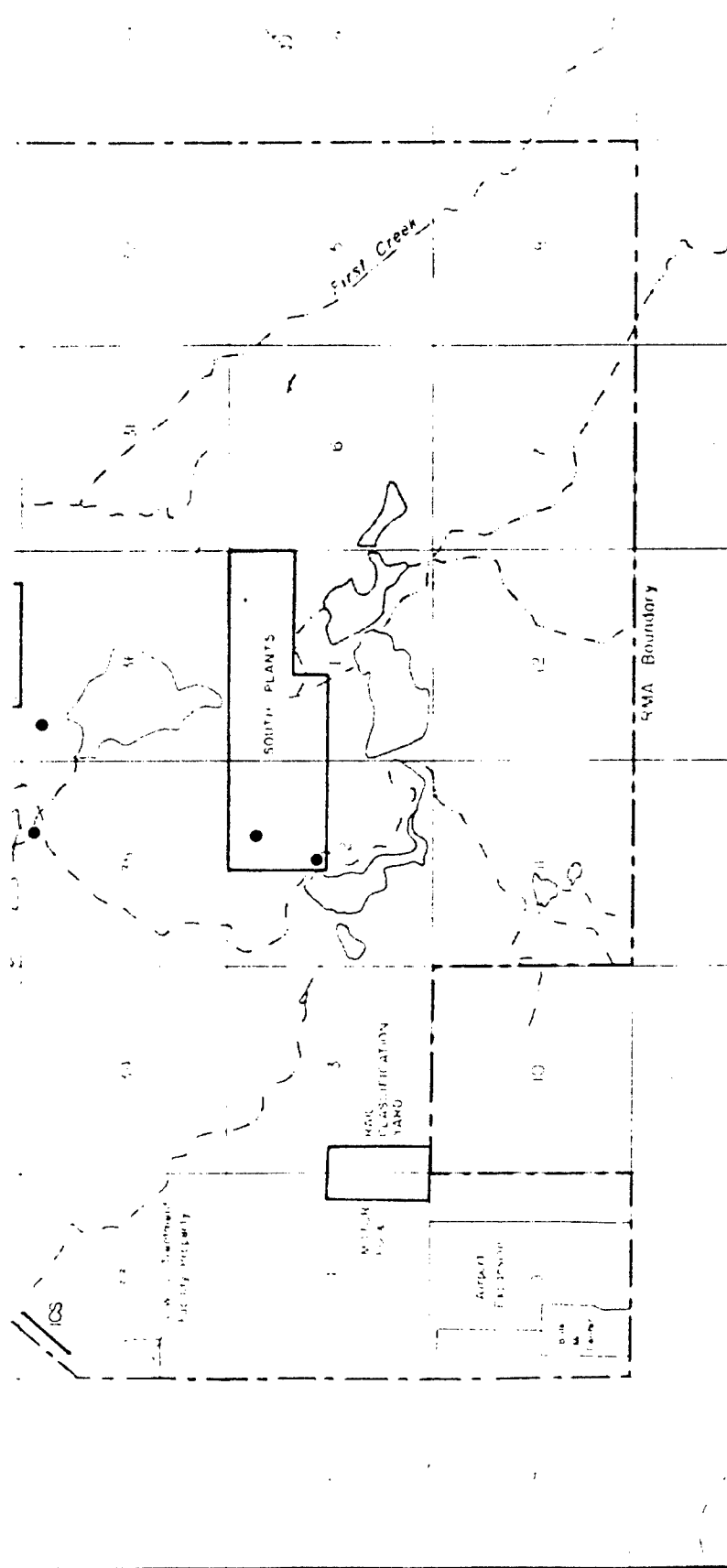
Areal Extent of Organic Analytes
Denver Formation Zone A

Prepared by: R.L. Stollar & Associates Inc.

Source: Compiled from concentration maps in Appendix D and F.







Explanation

- Isolated Detection

Prepared for:

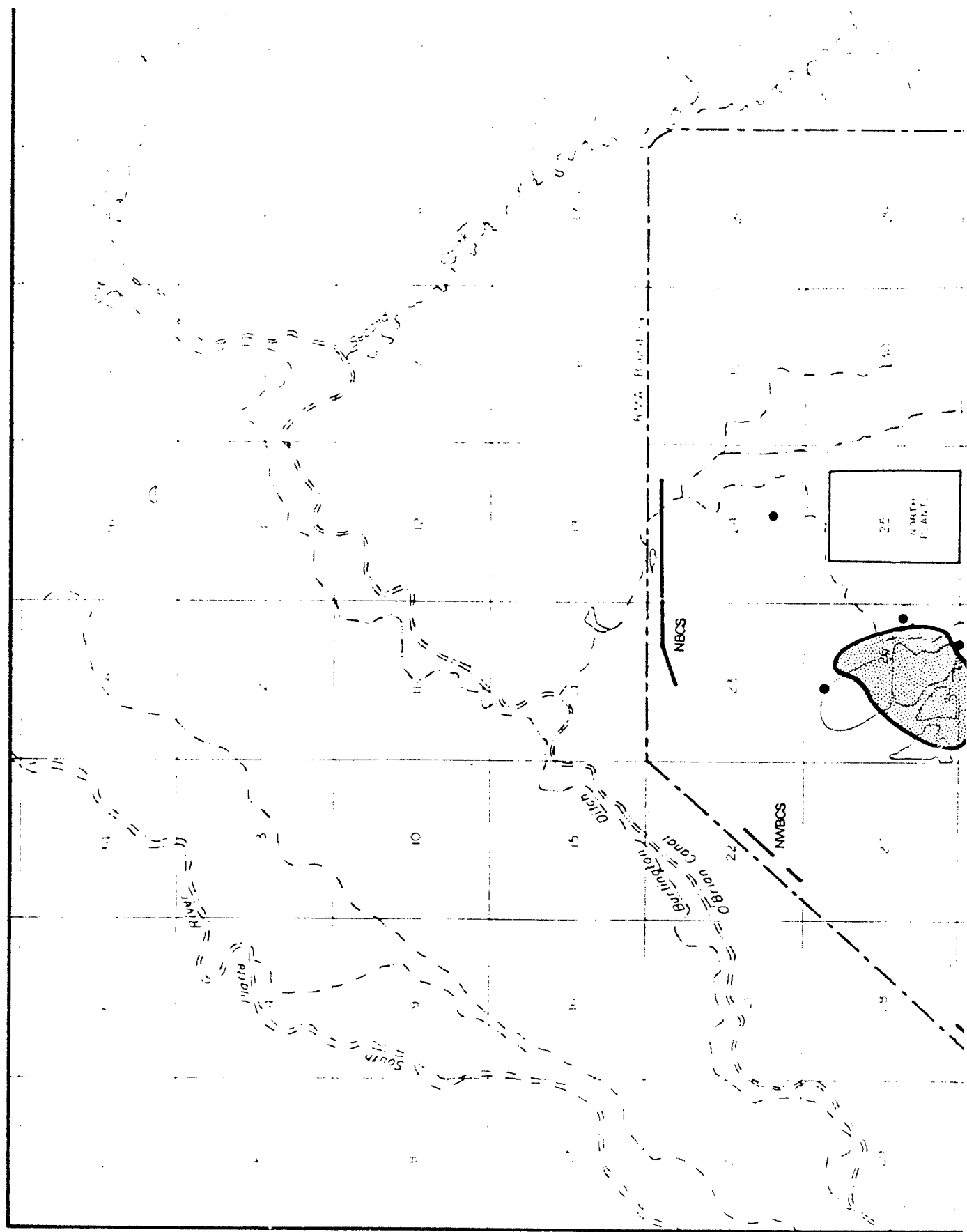
Program Manager's Office for
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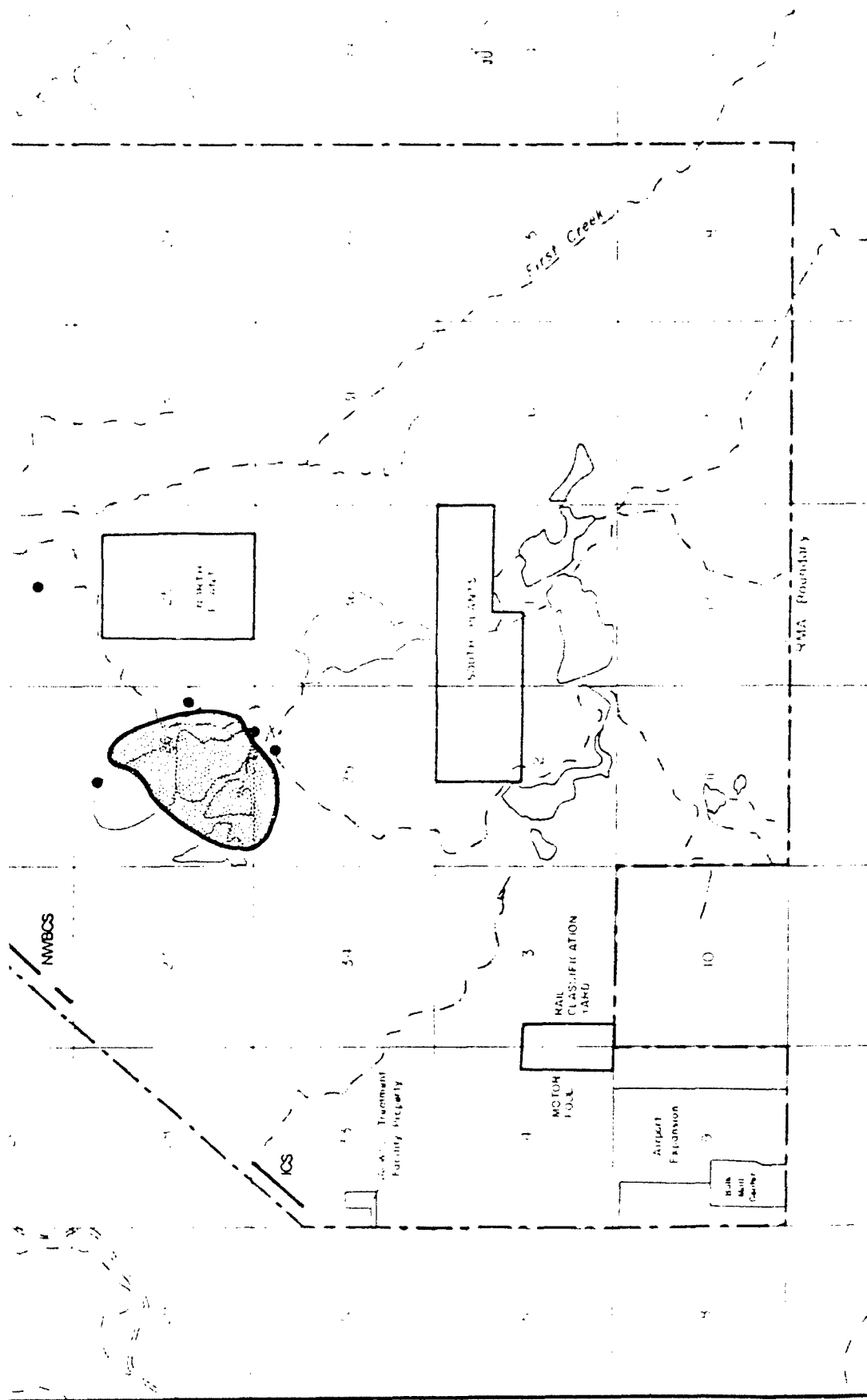
FIGURE 3.22

Areal Extent of Organic Analytes
Denver Formation Zone 1U

Prepared by: R.L. Stollar & Associates Inc.

Source: Compiled from concentration maps in Appendix D and F.





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Rocky Mountain Arsenal Cleanup
Aberdeen Proving Ground, Maryland

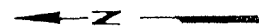
FIGURE 3.23

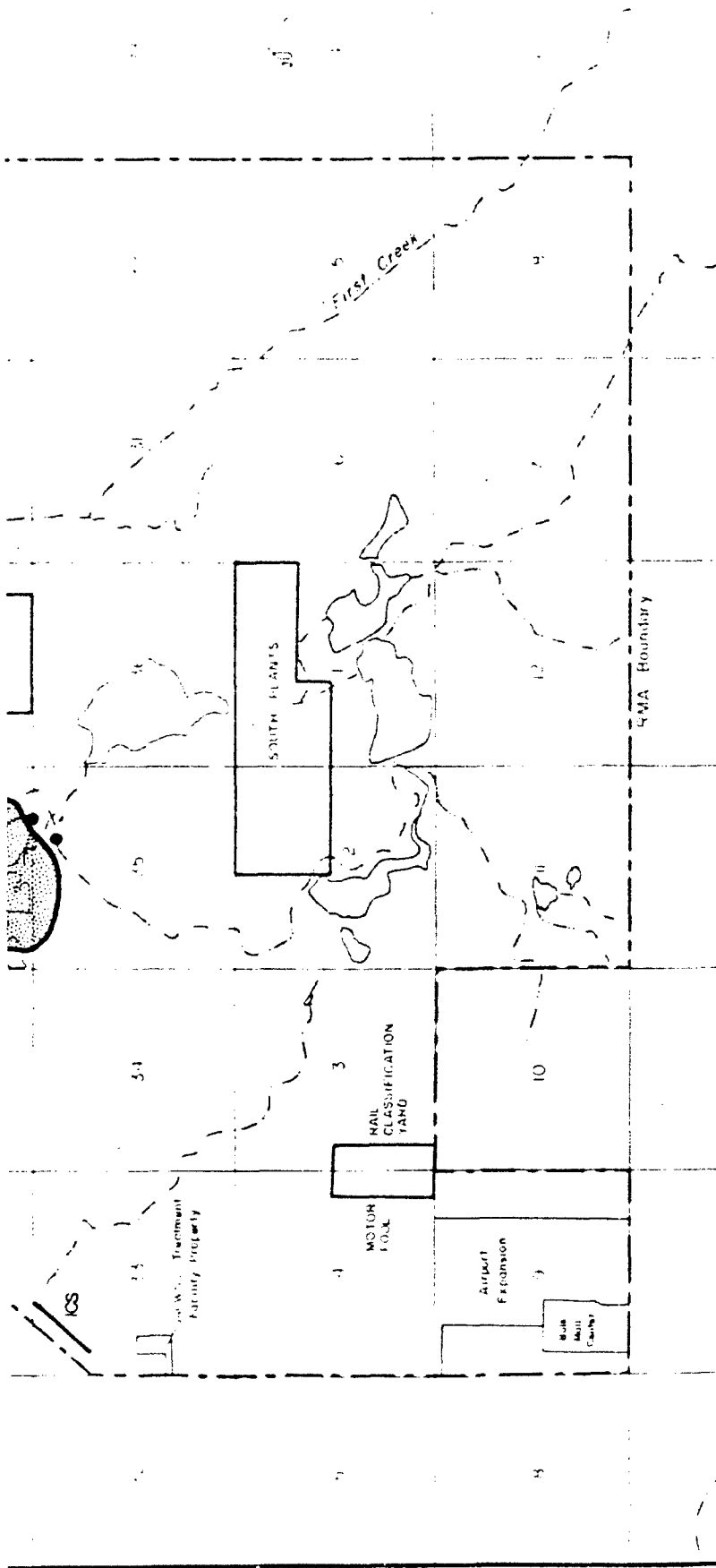
Explanation

Extent of organic analytes



Isolated Detection





Explanation

Extent of organic analytes

Isolated Detection

Prepared for:

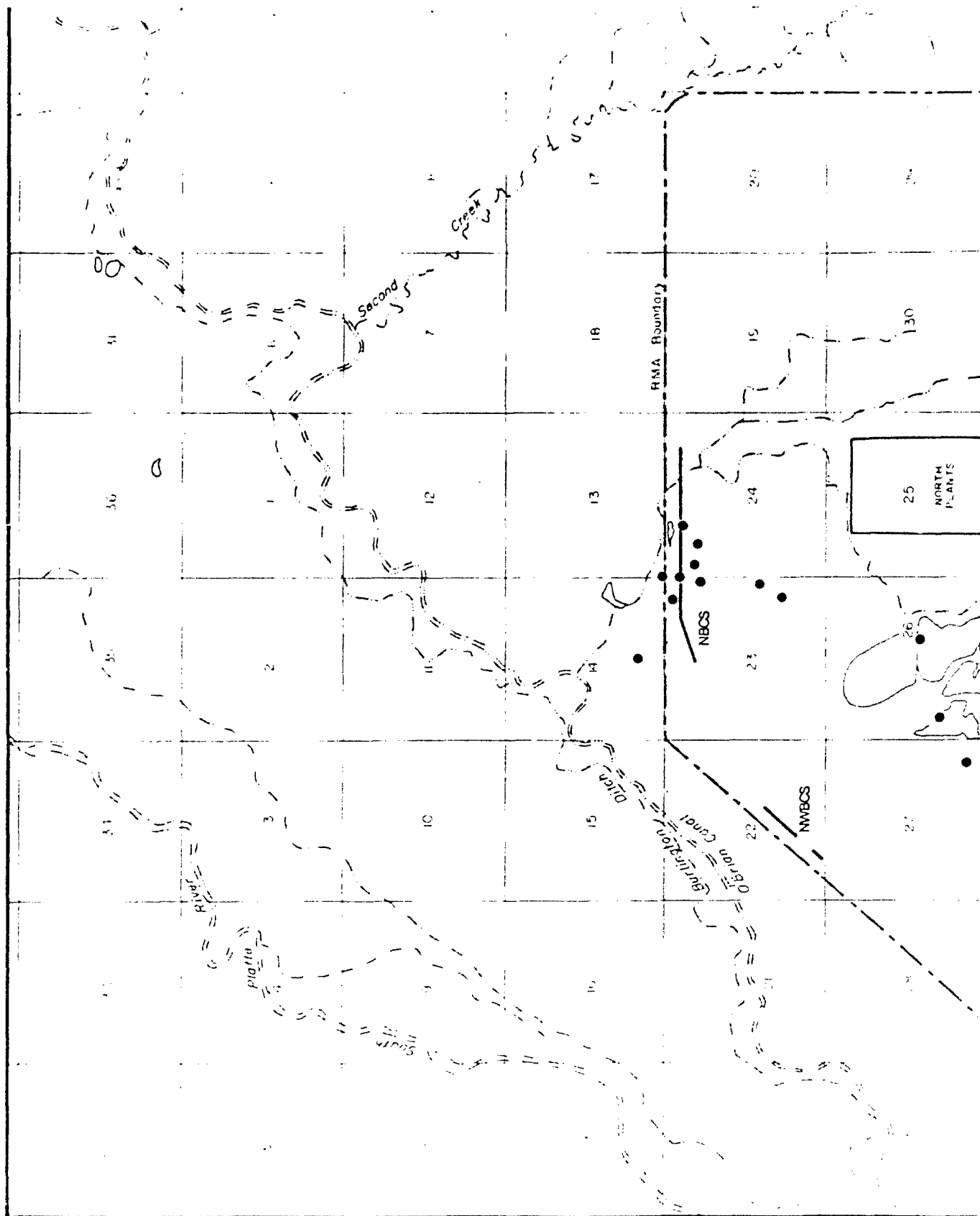
Program Manager's Office for
Rocky Mountain Arsenal Cleanup
Aberdeen Proving Ground, Maryland

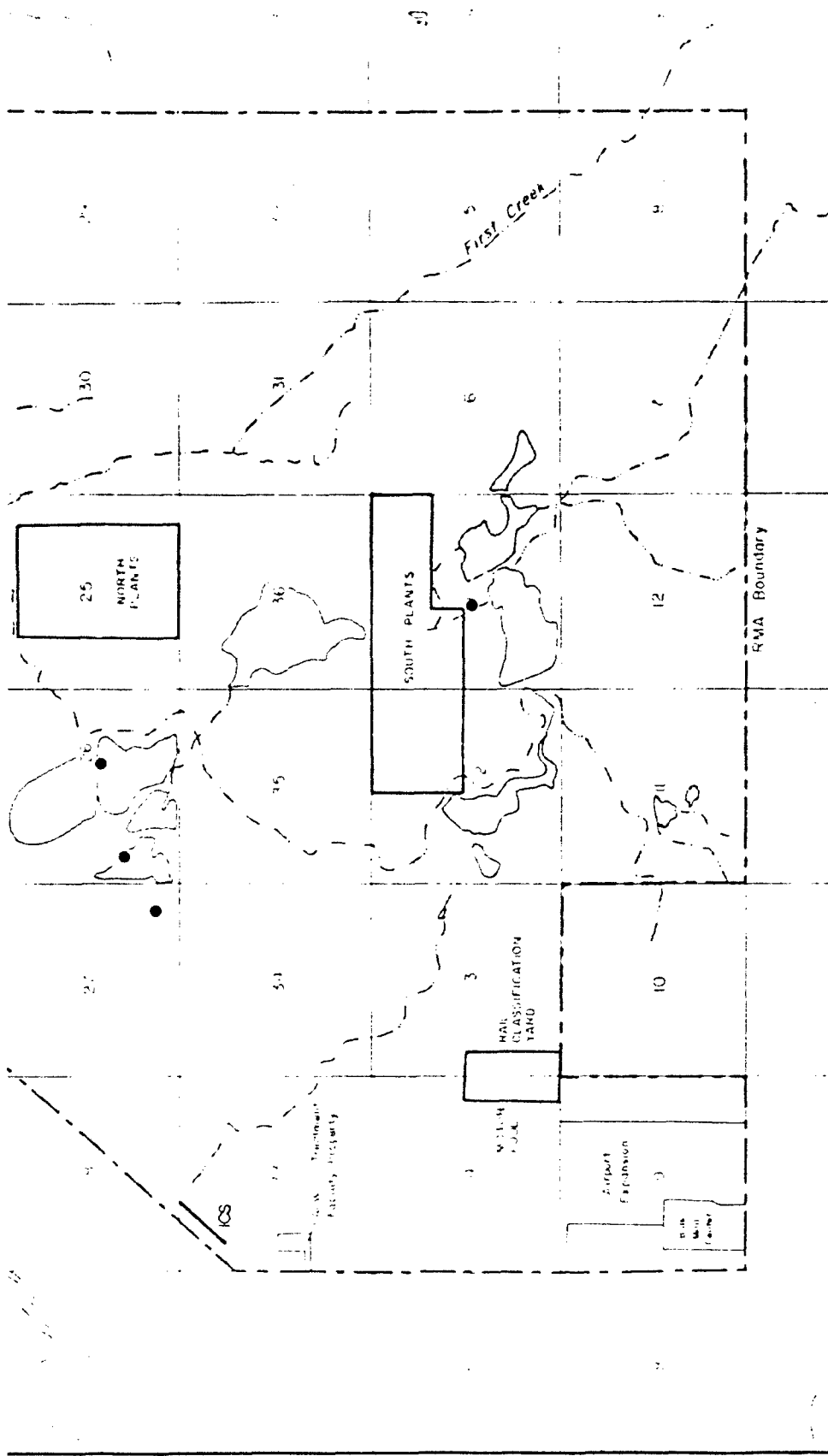
FIGURE 3.23

Areal Extent of Organic Analytes
Denver Formation Zone I

Prepared by: R.L. Stollar & Associates Inc.

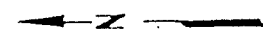
Source : Compiled from concentration maps in Appendix D and F.





Explanation

- Isolated Detection

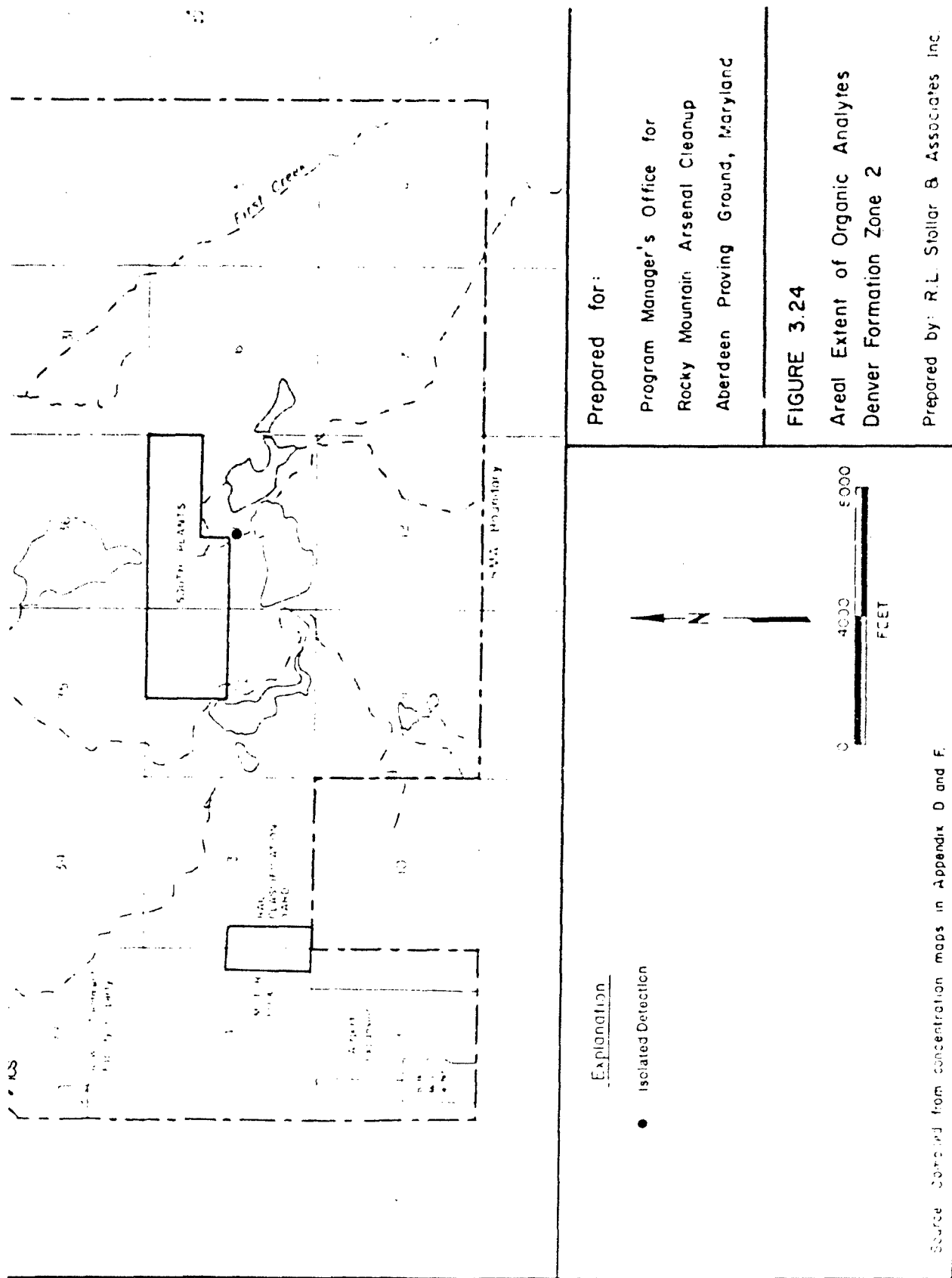


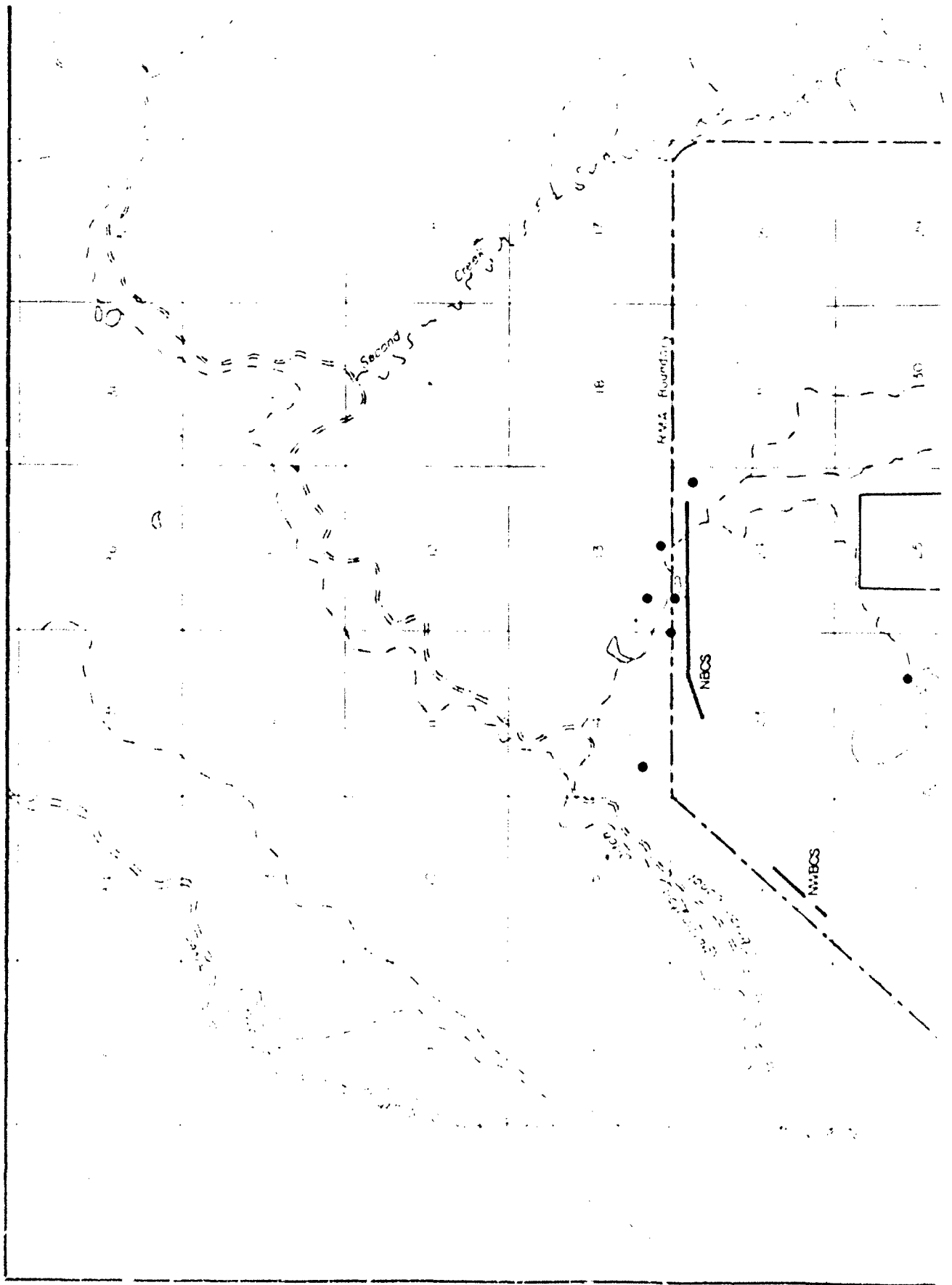
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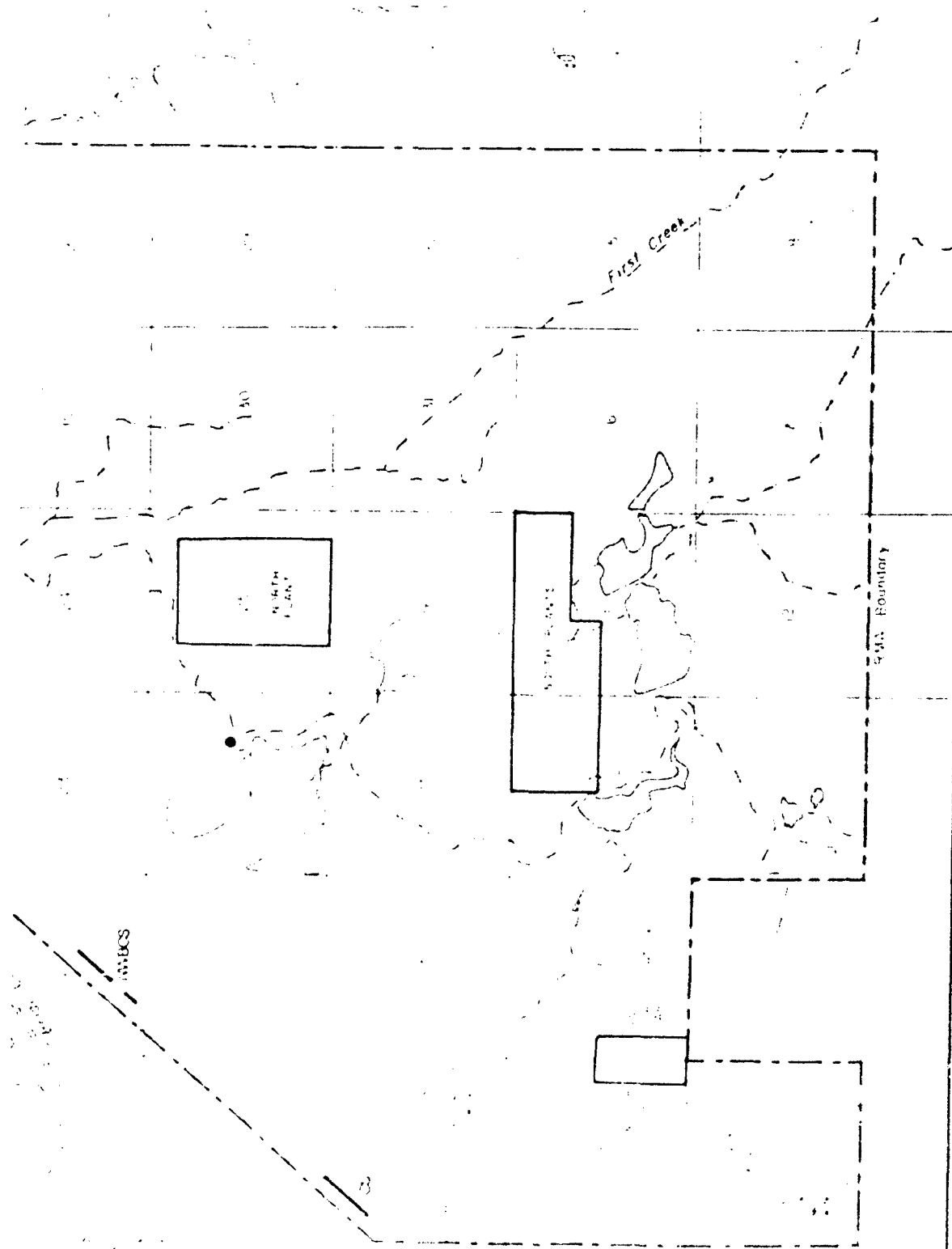
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FIGURE 3.24

Areal Extent of Organic Analytes
Denver Formation Zone 2





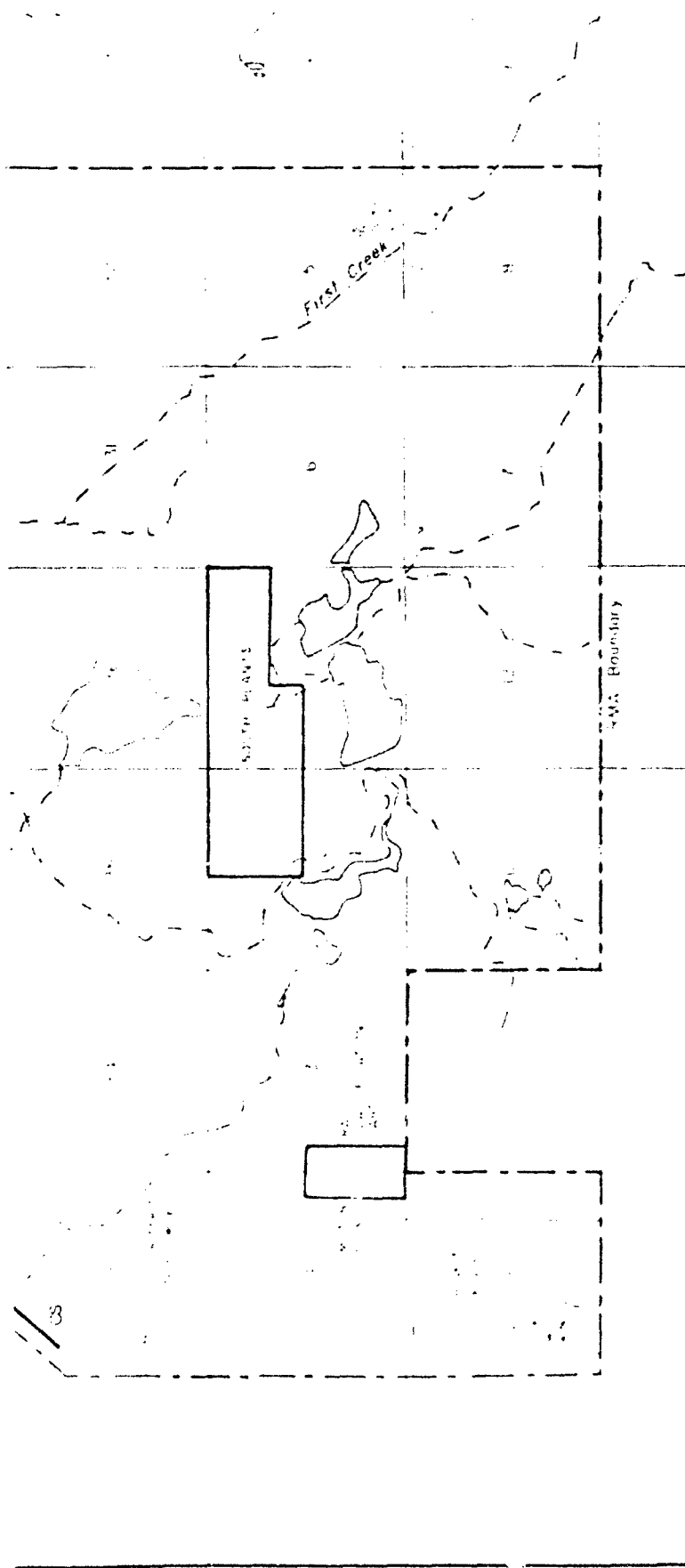


Isolated Detection

Isolated Detection

Prepared for:

Program Manager's Office for
Rocky Mountain Arsenal Cleanup
Aberdeen Proving Ground, Maryland



Explanation

- Isolated Detection

Prepared for:

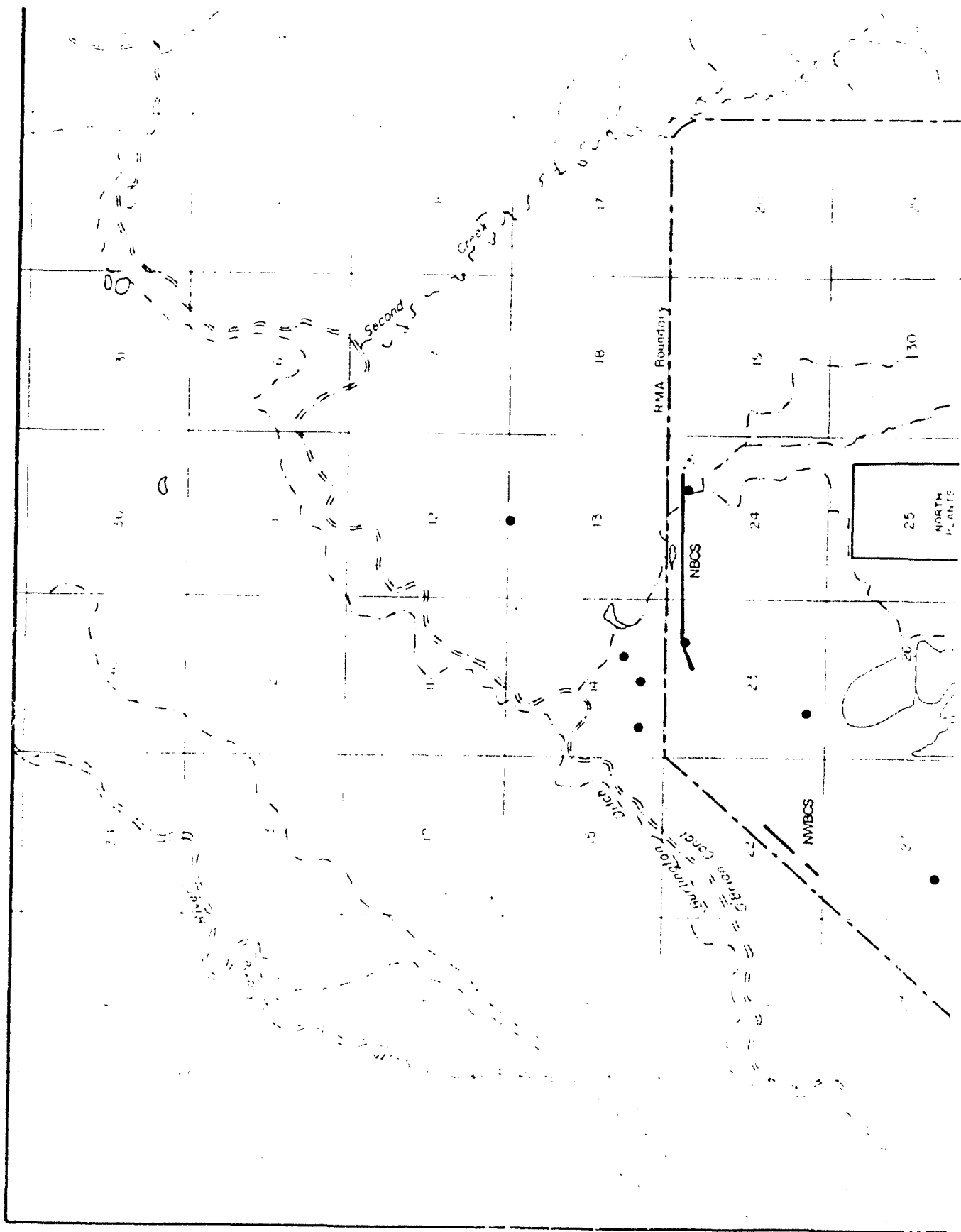
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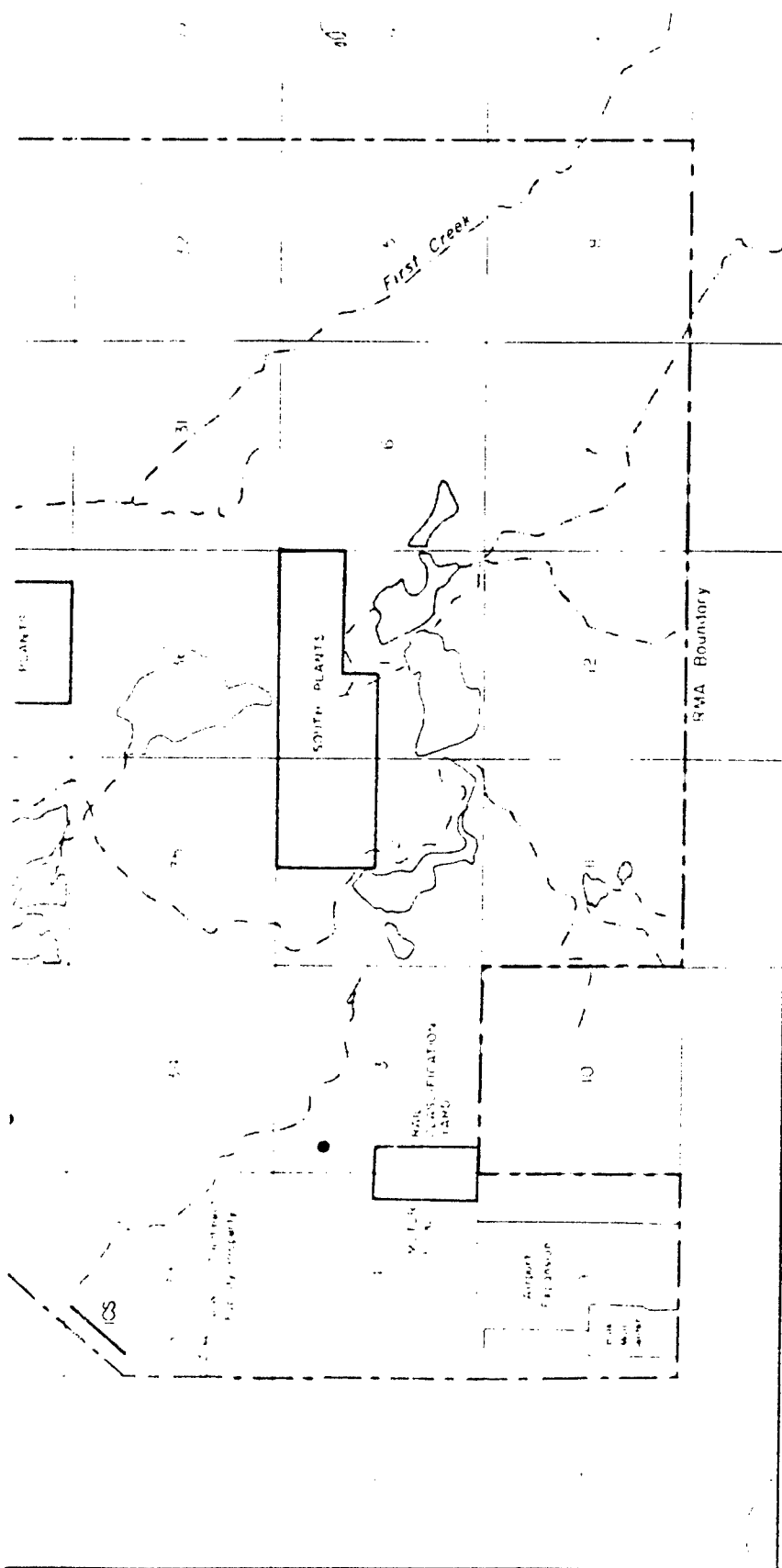
FIGURE 3.25

Areal Extent of Organic Analytes
Denver Formation Zone 3

Prepared by: R.L. Stollar & Associates Inc.

Isolated Detection from concentration maps in Appendix D and F.





Explanation

- Isolated Detection

Prepared for:

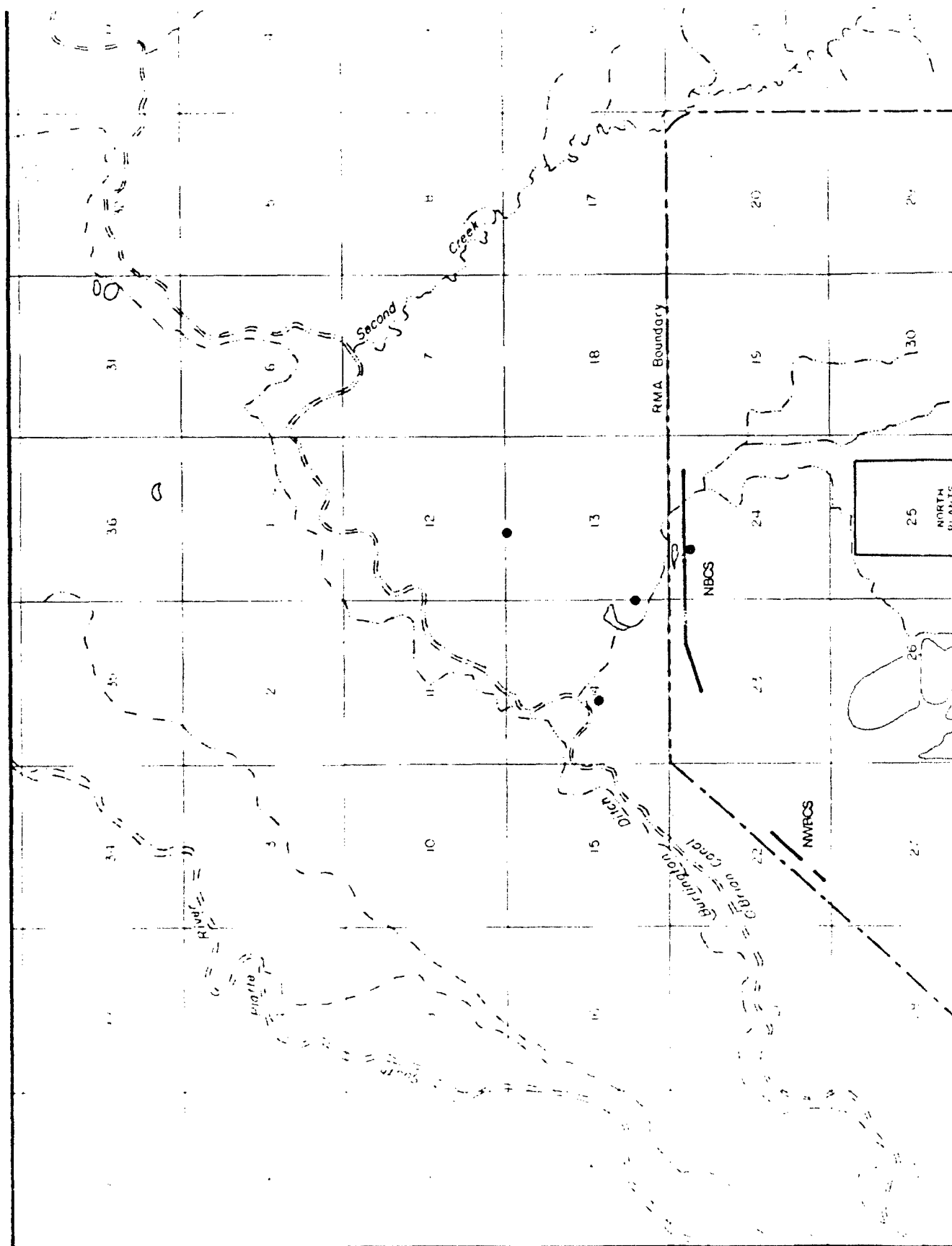
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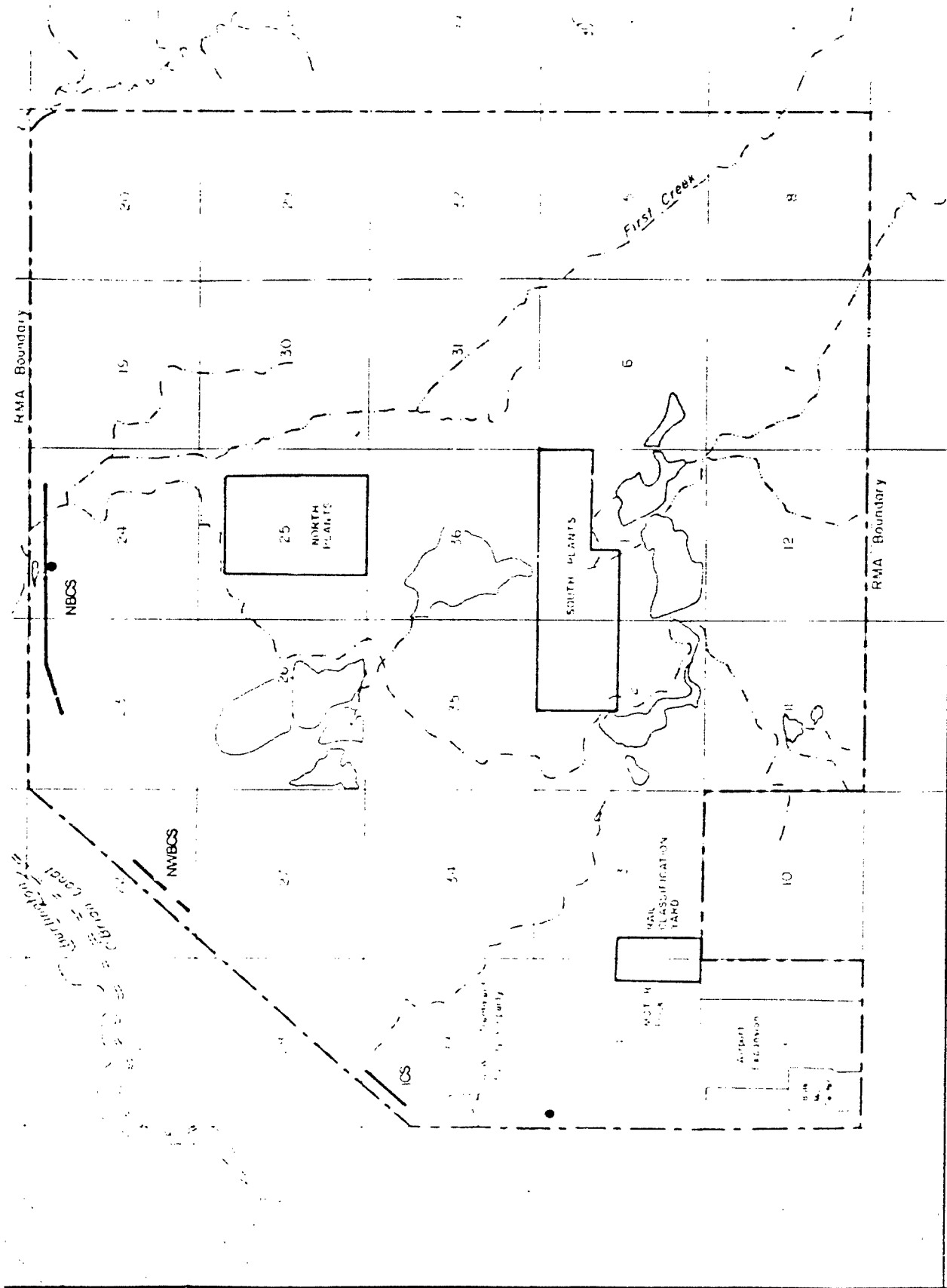
FIGURE 3.26

Areal Extent of Organic Analytes
Denver Formation Zone 4

Prepared by: R.L. Stollar & Associates Inc.

Source: Compiled from concentration maps in Appendix D and F.



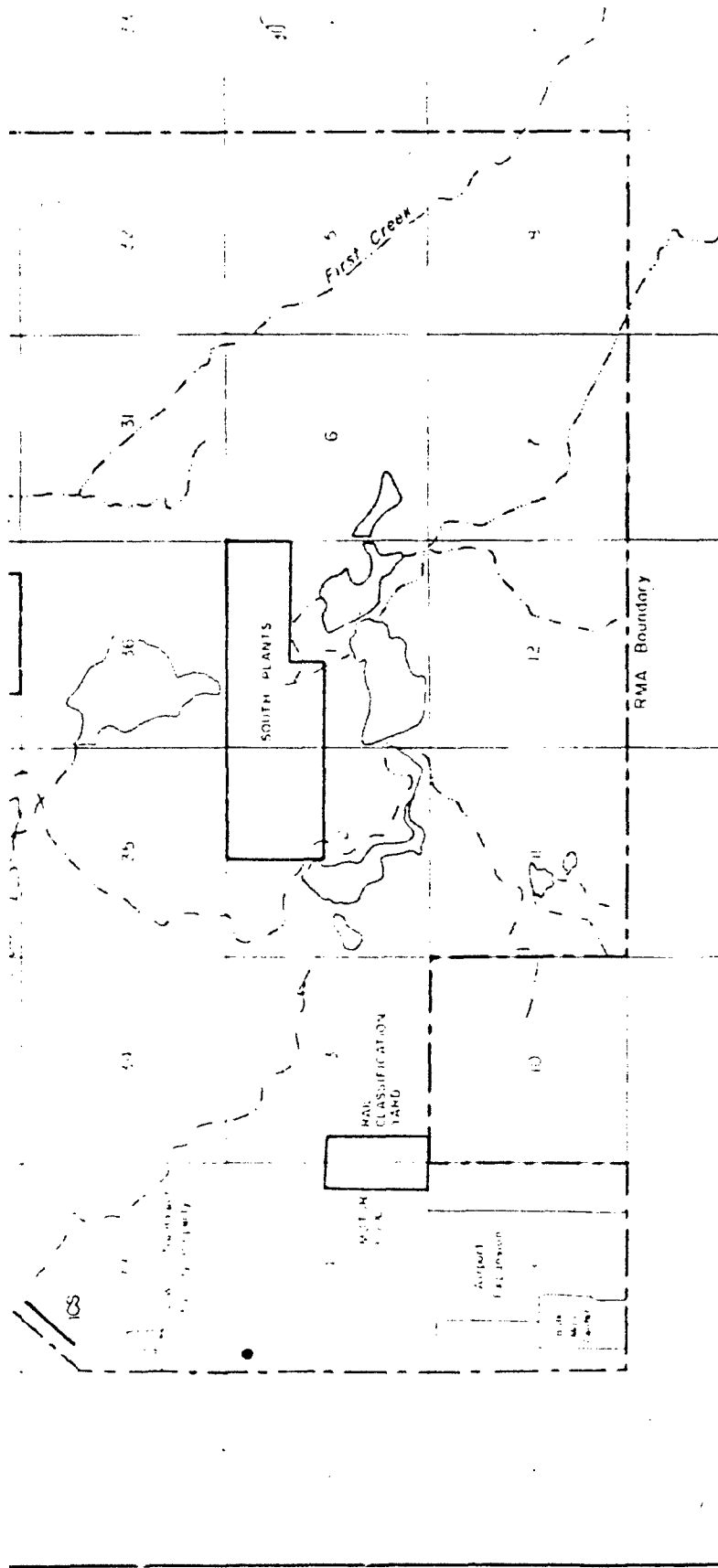


Prepared for:
 Program Manager's Office for
 Rocky Mountain Arsenal Cleanup



Explanation

● Isolated Detection



Explanation

- Isolated Detection

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Aberdeen Proving Ground, Maryland

FIGURE 3.27

Areal Extent of Organic Analytes
Denver Formation Zones 5 and 6

Prepared by: R.L. Stollar & Associates Inc.

Source : Compiled from concentration maps in Appendix D and F.

4.0 CONTAMINATION ASSESSMENT

The objectives of the Water Remediation Investigation contamination assessment at RMA are:

- o to identify sources of groundwater and surface water contaminants,
- o to describe mechanisms whereby contaminants may be introduced to water, and
- o to develop conceptual models for migration and alteration of contaminants in water.

In combination with hydrogeologic and water quality data available at RMA, the assessment provides sufficient hydrologic information to begin evaluating the feasibility of remedial action alternatives for contaminated water.

4.1 Hydrologic Mechanisms for Contamination of Surface Water

Surface water features at RMA include lakes, ponds, basins, canals, ditches, and natural depressions. Several of these features such as First Creek, ponds within Basin A, the Sewage Treatment Plant tributary to First Creek, and Sand Creek Lateral are potential contaminant pathways or are areas where surface water contaminants have been detected.

The rates at which contaminants can migrate in surface water are far greater than in groundwater. It is important to consider surface water flow when evaluating groundwater contaminant migration rates. For example, the Sand Creek Lateral was used to deliver South Plants waste to the basins in Section 26. The basins are located one mile north of South Plants; therefore, calculations of migration rates from South Plants must consider that contaminants were introduced to the groundwater in two or more locations during the same general time period.

Contaminants may enter the surface water by flushing and dissolving contaminants from surrounding soil, eroding and transporting contaminated soils and materials, or by the discharge of contaminated groundwater to the surface water. The erosion of contaminants into ditches, canals, ponds, and lakes is a major mechanism of contaminant migration during thunderstorms and snow melt. Thunderstorms can be very localized resulting in contaminant migration in some portions of RMA and not in others on the

same day. Because large fluctuations in temperature are common at RMA, conditions for snow melt may occur from October to April. Snow melt provides a widespread distribution of runoff throughout RMA. If temperatures remain near freezing and melting is slow, the potential for erosion of contaminated soils which are not in ditches or canals is low.

A wide range of contaminants have been detected in the surface water at RMA. These contaminants are either carried in solution by surface water; carried by surface water as bed load in streams, canals, and ditches; or migrate as suspended load in the water.

Several processes decrease the relative concentrations of contaminants in surface water. Contaminant concentrations in a ditch or canal may be diluted by the influx of relatively clean water from an entering tributary. Concentrations also may be reduced due to volatilization, degradation, or sorption of contaminants onto channel sediments. The addition of rain water and snow melt may also dilute contaminant concentrations.

Contaminant concentrations may increase during storm events as contaminated soils or materials are introduced to surface water. Where surface water collects in ponds or depressions for several days following a storm, evaporation may increase contaminant concentrations. An increase in contaminant levels has also been recognized in an off-post reach of First Creek near the north boundary of RMA when stream flow is low. Groundwater discharges into First Creek in this area. When flow rates are high, contaminants are diluted, the relative hydraulic heads between the creek and groundwater are reversed, and First Creek loses fresh water to the groundwater. Infiltration of surface water downward to the groundwater locally affects groundwater flow directions and rates, and changes contaminant levels in the groundwater.

4.2 Hydrologic Mechanisms for the Introduction of Contaminants to Groundwater

There are four mechanisms by which contaminants migrate from a source to the groundwater system at RMA. The four mechanisms are: migration in the unsaturated zone, direct migration from sources beneath or at the water table, introduction along improperly constructed well bores and hydraulic interchange of surface water and groundwater. Water level fluctuations can cause changes in the relative magnitudes of each mechanism.

Migration in the Unsaturated Zone

Water moving downward through the unsaturated zone will mobilize chemicals in the soil. In areas where the rate of water infiltration exceeds the rate of evaporation, the percolating water and any dissolved chemicals will reach the water table. In addition to dissolution of chemicals in the unsaturated zone, a substantial liquid contaminant spill could reach the water table by percolation.

Long-term evaporation at RMA exceeds precipitation. For this reason, contaminant migration through the unsaturated zone is likely only during periods of greater than average precipitation, during snowmelt, or where water accumulates at land surface. Regional groundwater budgets have been used to estimate effective distributed rates of recharge (HLA, Written Communication 1988). Values typically range from 0.06 to 0.13 ft/yr.

Direct Migration

Contaminant sources located below the water table are in direct hydraulic connection with the groundwater system and will migrate with groundwater. Examples of sources for direct migration of contaminants are underground storage tanks, transfer pipelines, sewers, sumps, basins, ditches, disposal pits, and building structures.

Introduction Along Improperly Constructed Wells

Migration may occur from a source through well bores or well clusters that are not properly closed or sealed. Interaquifer contamination along well bores can occur if wells are open to several aquifers of differing hydraulic head. Contaminants in the aquifer with greatest head will move through the well bore to other aquifers.

Hydraulic Interchange of Surface Water and Groundwater

Migration of contaminated surface water in streams, canals, lakes and basins will occur if the head of the surface water feature is greater than the water table. Migration will occur by saturated flow if the water table rises above the bottom of the surface water feature. If the water table is below the bottom of the surface water feature, migration will occur through the unsaturated zone.

4.3 Hydrologic Model of Groundwater Flow and Contaminant Migration

Groundwater is the primary concern of this contamination assessment because it has been the principal medium for off-post transport of contaminants. In Section 2.0, two major groundwater flow systems are described. The first is the Unconfined Flow System which comprises the saturated alluvium and upper Denver Formation where alluvium is unsaturated. The Unconfined Flow System is conceptualized to be laterally continuous across the RMA study area. The second system, underlying the Unconfined Flow System, is the Denver aquifer, which contains groundwater flowing through confined sandstone and lignitic strata that are interbedded with shales and claystones of relatively low hydraulic conductivity.

The greatest mass of contaminants within the RMA study area is contained within the Unconfined Flow System. The Unconfined Flow System is in direct contact with several chemical source areas and is responsible for the transport of the majority of the contaminants both within and adjacent to the RMA. Due to the large mass of contaminants present, the Unconfined Flow System has a high priority in site remediation.

4.3.1 Conceptual Model of Groundwater Flow

A conceptual model of groundwater flow at RMA has been developed that includes lateral flow within the Unconfined Flow System, vertical interchange of water between the Unconfined Flow System and the Denver aquifer, as well as lateral and vertical flow within the Denver. A complete description of the conceptual model is given in Section 2.4 through 2.6 and supporting information is provided in Appendix F, Section 2.0. Only those components of the conceptual model that are relevant to contaminant migration are summarized in this section.

Unconfined Flow System

The Unconfined Flow System is composed of saturated alluvium, some areas of weathered Denver Formation directly below saturated alluvium, and shallow weathered Denver Formation in areas of unsaturated alluvium. Although the Unconfined Flow System is areally continuous, there is a substantial difference between hydraulic conductivity of alluvium and Denver Formation. This difference greatly affects groundwater flow velocity and directions of contaminant transport.

The Unconfined Flow System has been divided into seven hydrogeologic units on the basis of similarities in lithology and aquifer test results. Although there is substantial variation within each unit, hydraulic conductivity of unconfined Denver Formation is one to two orders of magnitude less than the eolian unit and two to three orders of magnitude less than other units. Figure 2.3 shows the areal distribution for each hydrogeologic unit and representative hydraulic conductivity estimates for each unit.

Because the unconfined Denver Formation is significantly less permeable than unconsolidated materials, the Denver will tend to act as a partial barrier to lateral flow in areas of unsaturated alluvium. However, groundwater flow laterally into the unconfined Denver Formation is possible locally where the Denver Formation consists of sandstone or fractured rock. Within alluvial materials, larger hydraulic conductivity and greater saturated thickness tend to occur within paleochannel deposits.

Horizontal hydraulic gradients within the Unconfined Flow System were assessed using the Third Quarter FY87 Water-Table Map (Figure 2.4). Spatial variations in gradient are dependent largely on topography, saturated thickness, bedrock surface configuration, and hydraulic conductivity. Streamlines indicating groundwater flow directions have been drawn perpendicular to the water table contours in selected areas (Figure 4.1).

Sources of water to the Unconfined Flow System include seepage from surface water bodies, recharge from irrigation and precipitation, groundwater inflow along southern and eastern study area boundaries and flow from subcropping units of the confined Denver aquifer (Table 4.1). Discharge from the Unconfined Flow System occurs as lateral flow northwest toward the South Platte River, seepage to three lakes, pumpage by wells, and vertical flow into the confined Denver aquifer. Methods for estimating surface water seepage, recharge of irrigation and precipitation, and pumpage are described in Appendix F, Section 2.4.3. Groundwater flow into or out of the Unconfined Flow System was estimated using Darcy's law applied to segments of the Water Remedial Investigation study area boundary. Darcy's law computations were based on best estimates of hydraulic conductivity (Figure 2.3), saturated thickness (Figure 2.2), and hydraulic gradients extrapolated from Figure 2.4.

Table 4.1 Recharge/Discharge Relationships for the Unconfined Flow System

Component	Estimated Value (ac-ft/yr)
<u>RECHARGE TO GROUNDWATER UFS</u>	
Precipitation	630
Irrigation	6,750
Subcropping Denver Fm	600
Uvalda Interceptor	360
First Creek (on-post)	300
First Creek (off-post)	320
Highline Lateral	690
Fulton Ditch	4,020
Burlington Ditch	5,300
O'Brian Canal	13,100
Lower Derby Lake	480
Havana Pond	1,300
Other Surface Water Features	320
Groundwater Flow into WRI Study Area	5,000
Total Recharge:	39,170
<u>DISCHARGE FROM GROUNDWATER UFS</u>	
Lakes Ladora and Mary	70
Gun Club Pond	30
South Adams County Wells	3,900
Groundwater Flow into Denver Fm	170
Groundwater Flow to the South Platte River	35,000
Total Discharge:	39,170

Denver Aquifer

The Denver aquifer consists of interconnected beds of permeable sandstone and lignitic material and relatively impermeable claystone. In parts of the Denver Formation close to the bedrock-alluvial contact, secondary permeability may exist within the claystone, and hydraulic interchange between the Unconfined Flow System and Denver aquifer may be enhanced.

The Denver aquifer has been differentiated into stratigraphic units on the basis of lithologic description (Appendix F, subsection 2.2.3). Sequences containing a large proportion of sandstone and lignitic strata have been interpreted as units with relatively high hydraulic conductivity. Sequences composed primarily of claystone, clayshale, and volcanoclastics have been interpreted as units with low hydraulic conductivity. Individual sandstones are highly lenticular and cannot be correlated over significant distances. However, stratigraphic units commonly can be correlated at the scale of the study area (Plates 1 and 2).

Hydraulic conductivity varies spatially and reflects variations in lithology. Hydraulic conductivity of the shale and claystone matrix is low; it is probably 10^{-2} to 10^{-4} ft/d. In contrast, hydraulic conductivity for sandstone in the Denver aquifer has been estimated by slug-test analyses to range from 0.03 to 3 ft/d. Values less than 0.3 are typical of silty sandstone. Values from pumping tests range from 1.1 to 7.7 ft/d. Estimates of hydraulic conductivity for lignitic beds that have been fractured are not available. However, flow-model analyses indicate that the hydraulic conductivity of lignitic beds may be an order of magnitude greater than the hydraulic conductivity of sandstone.

Vertical head gradients in the Denver aquifer generally indicate downward potential for flow and horizontal gradients generally indicate horizontal potential for flow from southeast toward northwest. Based on these observations, a conceptual model of regional flow has been developed in which water moves downward from the Unconfined Flow System through strata with relatively low hydraulic conductivity into predominantly sandstone and lignite units of the Denver aquifer. The rate of vertical movement per unit area probably is small. Water in sandstone and lignite units generally moves laterally toward the northwest and probably returns to the Unconfined Flow System where the units subcrop.

Local gradients vary substantially from overall regional trends. As a result, localized flow paths are common in the Denver aquifer. Localized recharge and discharge occurs in areas where sandstone or other permeable material of the Denver aquifer is in contact with the Unconfined Flow System and the elevation of the bedrock surface varies appreciably in a short distance. Longer flow paths may occur in areas where vertical hydraulic conductivity is sufficiently large to permit deeper circulation of water.

4.3.2 Numerical Models of Groundwater Flow

Numerical models of groundwater flow in the vicinity of RMA have been developed to evaluate components of the conceptual model and to refine estimates of hydraulic conductivity and other aquifer characteristics. Separate models of flow in the Unconfined Flow System and Denver aquifer have been developed. A detailed description of the numerical models, including theory, input data, calibration procedure, and results, is given in HLA (Written Communication, 1988). Only results and conclusions are presented in this report.

Unconfined Flow System

The numerical model represents steady-state conditions in the Unconfined Flow System corresponding to 1987 hydrogeologic data. Consequently, the model may not be appropriate for simulation of historical conditions where substantial water level fluctuations saturated alluvial deposits that currently are unsaturated. Water level fluctuations that affect hydraulic relations between the Unconfined Flow System and the confined Denver aquifer cannot be simulated with the existing model.

Initial simulations of flow in the Unconfined Flow System were based on estimates of hydraulic conductivity, hydrogeologic unit boundaries, and recharge and discharge given previously in Section 2.0 of this report. Model calibration consisted of adjusting hydraulic parameters, primarily hydraulic conductivity, until simulated hydraulic head adequately reproduced measured water levels. With few exceptions, model calibration was achieved without major modifications to initial estimates. Calibration results indicate that the model is sufficiently reliable for purposes of the Remedial Investigation. Additional refinement in parameter estimates may be needed to meet objectives of the Feasibility Studies.

Model results are consistent with the concept that paleochannels and terrace deposits generally convey higher volumes of water than interfluvial zones. The axes of most paleochannels trend from southeast to northwest and are consistent with the general direction of groundwater movement. Material in the paleochannels and terrace deposits near the South Platte River are characterized by higher hydraulic conductivity than exists in Unconfined Flow System materials southeast of the river terraces. As a result, hydraulic gradients in the river terraces are less steep than in other areas.

Efforts to simulate flow in the Unconfined Flow System were unsuccessful unless recharge from subcropping sandstone in the Denver Formation was specified. Sensitivity analyses with the numerical model of the Unconfined Flow System show that the overall effect of hydraulic interchange between the Unconfined Flow System and the Denver aquifer is small. However the relationship is hydraulically important in areas of relatively small lateral flow. These areas generally are located in the vicinity of South Plants and Basins A through F. These areas are important because they contain the majority of contaminant source areas.

Hydraulic conductivity estimates in the Basin A Neck and areas immediately downgradient obtained during model calibration are smaller than values indicated in this report (Figure 2.3). If the model estimates are reliable, flow to the Northwest Boundary Containment System from Basin A Neck are less than originally inferred. The comparison between simulated and measured hydraulic head is least favorable in the vicinity of Basin A Neck.

The numerical model indicates that flow to the northwestern boundary of RMA from the Basin A Neck area is lower today than in past years. Flow currently is estimated to be 0.15 cfs and reflects a period when Basins A through E have not been used for waste storage. Robson (1977) estimated flow of 0.77 cfs for this area from 1952 to 1975. Waste fluids from RMA were released to Basins A through E during part of this earlier period.

Sensitivity analyses conducted with the numerical model have identified areas where uncertainty in hydraulic conductivity estimates have a large effect on model results. The areas of greatest sensitivity are mostly south and east of RMA. Large sensitivity also exists in areas of low flow near South Plants and Basins A through F. For purposes of the Remedial Investigation, results of the sensitivity analyses indicate that the model is sufficiently reliable.

Denver Aquifer

A cross-section numerical model was developed to gain a better understanding of the mechanisms of flow within the Denver aquifer, rather than refining hydraulic parameter values at particular locations. This included evaluating the conceptualization of layered hydrogeologic units, the degree of confinement provided by clayshale strata of the Denver Formation, and whether alternative conceptualizations of the hydrogeologic system were possible.

The cross-sectional flow model was constructed approximately along flow paths in the Denver aquifer from Upper Derby Lake to the Basin A Neck. The modeled flow region extended from the alluvium-bedrock contact to a depth of about 150 ft. The Unconfined Flow System was not specifically modeled in this study, but provided upper prescribed head boundary conditions to the modeled area. A variety of layered heterogeneous flow systems were hypothesized and steady-state flow through each system was simulated. As an alternative, the flow region was also modeled as a single homogeneous anisotropic material to evaluate whether this conceptualization might also be representative of the Denver aquifer.

Sensitivity analyses were performed by varying the hydraulic conductivity of materials and observing the effects of such changes on the distribution of hydraulic head within the flow system. The purpose was to define plausible ranges of hydraulic conductivity values and the ratios of hydraulic conductivity between different materials. Distributions of hydraulic head predicted by the model were compared with point measurements of hydraulic head from piezometers to evaluate the reliability of the input parameter values and the modeled geometries of hydrogeologic units. This differs from the calibration procedure used in the Unconfined Flow System numerical model, which was intended to arrive at "best estimate" parameter values. The findings in this cross-sectional model may not be applicable to other areas of RMA.

Results of the cross-sectional numerical model are summarized below:

- o A conceptual model based on layered material of differing hydraulic conductivity is more representative than a model which considers a single homogeneous

anisotropic material. However, layers of uniform hydraulic conductivity are not necessarily continuous across RMA.

- o Shale and claystone layers have vertical hydraulic conductivity in the range of 3×10^{-4} to 3×10^{-6} ft/day (10^{-7} to 10^{-9} cm/sec). This indicates that, where continuous, shale and claystone provide a high degree of confinement within the Denver aquifer.
- o The hydraulic conductivity of sandstone ranges from 0.3 to 3 ft/day (10^{-4} to 10^{-3} cm/sec), but a value closer to 3 ft/day (10^{-3} cm/sec) seems to be more representative in the modeled area.
- o Lignitic layers appear to have the highest hydraulic conductivity within the Denver aquifer. Lignite hydraulic conductivity may be on the order of 10 to 20 ft/day (4×10^{-3} to 7×10^{-3} cm/sec).

4.3.3 Conceptual Model of Contaminant Migration

Changes in contaminant concentrations in groundwater at RMA are due to advective transport, hydrodynamic dispersion, dilution, and chemical or physical reactions. Advection, dispersion, and dilution are related to groundwater flow and are discussed in this section of the report. Changes in contaminant concentration due to chemical or physical reactions are discussed in Section 4.4.

Contaminant migration due to the movement of water is described by advection and hydrodynamic dispersion. Advection is migration at the average rate of water molecules and is described by the average linear velocity of the groundwater. The average linear velocity is estimated as the product of hydraulic conductivity and hydraulic gradient divided by effective porosity. Hydrodynamic dispersion describes deviations from the average rate of migration. Hydrodynamic dispersion may be viewed as the result of tortuosity or small-scale variations in hydraulic conductivity along a flow path. In isotropic homogeneous material, hydrodynamic dispersion can be quantified by a dispersivity tensor with principle axes aligned parallel and perpendicular to the direction of flow. Models to describe hydrodynamic dispersion coefficients in anisotropic or heterogeneous material are more complex.

Changes in contaminant concentration due to dilution occur when water having a certain concentration of contaminant mixes with water having a different concentration. Qualitatively, areas of dilution are indicated by maps showing converging flow paths. Quantitatively, areas of dilution are indicated by mass balance calculations using flow models or flow net analyses.

Unconfined Flow System

Rates of migration due to advection depend on hydraulic conductivity, hydraulic gradient and effective porosity. Values of these parameters generally are site specific. Descriptions of migration due to advection along selected flow paths are given later in this report (Section 4.6). Descriptions of hydraulic conductivity and hydraulic gradients were given previously. Effective porosity of alluvial material and subcropping sandstone of the Unconfined Flow System should be approximately the same numerically as specific yield or bulk porosity. Values of bulk porosity in coarse-grained strata should range from 0.2 to 0.4. Values of bulk porosity in fine-grained strata should be less. Effective porosity estimates in weathered or fractured clayshale may be less than 0.01. Numerical models of contaminant migration in alluvial material at RMA have been developed successfully using effective porosity estimates of approximately 0.4 (Konikow, 1977; Robson, 1981).

Regional estimates of migration due to hydrodynamic dispersion have been made as part of numerical modeling studies. Hydrodynamic dispersion in alluvial material of the Unconfined Flow System appears to be similar to dispersion in isotropic homogeneous media. Regional estimates of dispersivity in the direction of flow are approximately 100 ft while dispersivity transverse to the direction of flow is approximately 30 ft (Konikow 1977; Robson, 1981).

Changes in solute concentration due to dilution are important in the vicinity of the South Platte River and associated alluvial terraces. Contaminated water migrating toward this area from RMA is diluted substantially by relatively uncontaminated water moving in terrace gravel parallel to the South Platte River. Much of the dilution occurs beyond the boundaries of RMA.

Dilution may have been an important mechanism for modifying contaminant concentrations beneath and north of Basin F. Relatively uncontaminated water diverted to Basin C in the past probably increased the rate of advective transport beneath Basin F toward the northern boundary of RMA. Enhanced recharge beneath Basin C caused water levels to rise and temporarily increased contaminant concentration by flushing contaminants that had accumulated previously above the water table. Following flushing of contaminants, enhanced recharge may have decreased contaminant concentrations by dilution in the vicinity of Basin C.

Denver Aquifer

Contamination of the Denver aquifer probably occurred by intergranular flow in areas where sandstone channels provide direct hydraulic connection with the Unconfined Flow System. For example, contamination of sandstone zone 1 in the Denver aquifer beneath Basin C probably occurred by intergranular flow. The rate of migration probably was enhanced by rising water levels in the Unconfined Flow System during periods when Basin C contained water.

This mechanism of vertical migration only is effective in explaining local areas of contamination within the upper-most permeable zones of the Denver aquifer. Within RMA, contamination has been observed in deeper sandstone zones as well as sandstone zones separated from the Unconfined Flow System by shale or claystone. Calculated rates of migration by intergranular flow are not sufficiently large to explain contamination in these intervals.

Contamination of deeper sandstone zones of the Denver aquifer probably occurred by vertical migration through fractured shale and claystone. Interconnected fractures are likely to form clusters near structural anomalies rather than being distributed uniformly throughout RMA. Contaminant migration through fracture clusters would result in irregular patterns of contamination in the Denver aquifer. Contamination would not occur uniformly beneath areas of the Unconfined flow System known to be contaminated. Instead, areas of contamination in the Denver aquifer would reflect the areal distribution of fracture clusters. Vertical migration through fractured shale and claystone also may result in contamination of several stratigraphic intervals of sandstone that are separated vertically by shale and claystone.

As in the Unconfined Flow System, rates of contaminant migration due to advection in the Denver aquifer are site-specific and are described for selected pathways in Section 4.6 of this report. Effective porosity of the Denver aquifer probably depends on the interconnected nature of individual sandstone lenses and other permeable strata. When contaminant migration occurs over substantial distances within a single sandstone channel or several highly interconnected sandstone lenses, the value of effective porosity probably approaches the value of bulk porosity for sandstone (0.05 to 0.3). When contaminant migration occurs in areas where sandstone lenses are not highly interconnected or if migration occurs in networks of fractures, effective porosity probably is substantially less than 0.05. Because connectivity of permeable sandstone and fractures in the Denver aquifer is less in the vertical direction than in horizontal directions, it is possible that effective porosity also is directionally dependent.

Because individual contaminant plumes in the Denver aquifer have not migrated over a large area, hydrodynamic dispersion characteristics are not well understood. Limitations in the understanding of advective transport in the Denver aquifer also have contributed to difficulties in describing dispersion. The anisotropic and heterogeneous nature of the Denver aquifer indicates that dispersion characteristics of the Denver aquifer probably are more complex than dispersion characteristics of the Unconfined Flow System.

Effects of dilution on contaminant concentration in the Denver aquifer would be most noticeable as contaminated water moves vertically. Water in the Denver aquifer moving horizontally along regional flow paths would dilute the contaminated water moving vertically.

4.4 Chemical Properties and Hydrochemical Processes Affecting Contaminant Migration

The purpose of this section is to describe physical and chemical properties and hydrochemical processes that affect contaminant migration at RMA. In addition to the effects of dilution described above, the predominant processes affecting changes in contaminant concentration are chemical and biological degradation, sorption, and volatilization.

Highly soluble target analytes are generally more mobile, are transported more readily in groundwater and surface water environments, and tend to be less persistent in soil

environments. Such highly soluble compounds also tend to be retained by soil matter less readily and tend to be more amenable to biodegradation.

Some organic compounds can volatilize from soil or water. The rate of volatilization is compound specific. Factors that control volatilization of organic compounds include solubility, molecular weight, vapor pressure and temperature.

Compound partitioning between soil and water, between soil and air, and between water and air also affects the mobility of that compound. Partitioning between air and other media is influenced by properties affecting volatilization described above. Partitioning of target compounds between soil and water is discussed in Section 4.4.2.

Several chemical processes contribute to the overall process of chemical transformation. The primary components of chemical transformation are hydrolysis and photolysis. During hydrolysis, an organic compound reacts with water forming the carbon-oxygen bond of a hydroxide ion. This commonly leads to elimination of a bond with the same carbon atom. With alteration in the chemical structure of the compound, the physical properties of the compound (i.e. solubility, volatility) and compound toxicity also change.

Photochemical processes include both direct photolysis in which the compound absorbs solar radiation and is transformed, and sensitized photolysis in which the energy which transforms an organic compound is derived from another species in solution. At RMA photolysis reactions may occur in surface water and, to a lesser extent, in surface soils.

Biodegradation is an additional mechanism by which RMA target compounds may be lost or transformed from soils and waters. Although very little is known of rates of biodegradation, a sufficient amount of historical data from RMA may be helpful in evaluating the possible utility of biodegradation processes in remediating present site conditions. Rates of biodegradation are dependent upon microbial tolerance to specific compounds and groups of compounds as food sources. Therefore, rates of biodegradation are dependent upon molecular characters and physiochemical properties.

4.4.1 Physical and Chemical Properties

To a great extent, the physical and chemical properties of target analytes are responsible for their rates of migration and degree of attenuation. The most important of the physical and chemical properties are physical state, specific gravity, solubility, vapor pressure, Henry's Law Constant (H_c), octanol/water partition coefficient (K_{ow}), and the soil-water distribution coefficient (K_d). These basic properties of the RMA target analytes are presented in Table 4.2.

The physical state of a compound (solid, liquid, or vapor) may influence its occurrence within a given system. Contaminants in RMA groundwater generally occur in a dissolved state. However, free organic phase liquids may be present in the saturated zone near South Plants, as indicated by very high aromatic concentrations in groundwater and historic spills of benzene (MKE, 1986, unpublished data). The potential presence of such organic contamination would not alter regional contaminant transport mechanisms but would act as a subsurface contaminant source.

The specific gravity of a dissolved contaminant (Table 4.2) probably will not affect regional contaminant distribution. The only instance in which specific gravity of a contaminant or contaminant mixture may have affected transport would be if free organic phase liquids or dense brines were introduced to the unsaturated or saturated zone. In such instances these dense liquids would tend to follow the topography of the first impermeable zone reached.

Aqueous solubility controls the maximum contaminant concentration that may occur in solution as well as the concentration released from a source area. Factors which influence solubility include temperature, dissolved solids, pH, and dissolved organic matter. Table 4.2 lists solubilities of select contaminants found in RMA waters. Aromatics and volatile halogenated organics are highly soluble while the pesticides are less soluble. Solubility of chloride and fluoride are high. Solubilities of other inorganic compounds such as arsenic are dependent on the oxidation and pH conditions of the system, and must be evaluated on a site-specific basis.

Table 4.2 Physicochemical Properties of Select RNA Contaminants
(Page 1 of 5)

Analyte	Specific Gravity (g/ml)	Solubility (mg/l)	Vapor Pressure (mm Hg)	Henry's Constant (H _c) (atm-m ³ /mol)	Log Octanol-Water Partition Coefficient	Retardation Distribution Coefficient	Environment Fate ²
Aldrin	1.6	.021	6.6x10 ⁻⁶	1.6x10 ⁻⁵	5.3-7.4	220	1361 Long lived in soil and water. Decomposes to dieldrin in soil (half life = 4-5 years). Biodegradation - highly persistent.
Benzene	0.88(20°C)	1,700	95(20°C)	5.6x10 ⁻³	2.0-2.1	0.16	2.0 Soil half life = approximately 1 month. Biodegradation, somewhat persistent.
Benzothiazole	1.2	572	.05	1.64x10 ⁻⁵	1.45-1.67	0.32	3.0 Biodegradation - high persistent.
Carbon Tetrachloride	1.6(20°C)	810	90(20°C)	2.4x10 ⁻²	2.64-2.83	0.73	5.5 Resistant to microbial degradation. Does not hydrolyze.
Chlordane	1.6(16°C)	.13	1x10 ⁻⁵ (25°C)	9.6x10 ⁻⁵	2.78-5.48	530	3278 Epoxidized to chlordene epoxide by soil bacteria. Slow reaction, resistant to decomposition, bioaccumulates.
Chlorobenzene	1.11(20°C)	450	11.7	3.72x10 ⁻³	2.84-2.98	1.34	9.3 Slowly microbially degraded. Biodegradation, persistent.
Chloroform	1.48(20°C)	8,300	151	2.87x10 ⁻³	1.90-1.97	0.47	3.9 Stable in the environment. Biodegradation. Highly persistent.
Chlorophenylmethyl sulfide	1.2	16	.05	6.4x10 ⁻⁴	3.2	4.25	27 Soil half life = > 6 months, oxidizes to analogous sulfone.
Chlorophenylmethyl sulfoxide	-	1,100	7.8x10 ⁻²	1.5x10 ⁻⁵	1.2	0.20	2.2 Soil half life = < 6 months, oxidizes to analogous sulfone.

Table 4.2 Physicochemical Properties of Select RMA Contaminants
(Page 2 of 5)

Analyte	Specific Gravity (g/ml)	Solubility (mg/l)	Vapor Pressure (mm Hg)	Henry's Constant (H _c) (atm-m ³ /mol)	Log Octanol-Water Partition Coefficient	Distribution Coefficient	Retardation Factor ¹	Environment Fate ²
Chlorophenylmethyl sulfone	-	910	3x10 ⁻³	8.0x10 ⁻⁶	1.3	0.24	2.5	Degraded by micro organisms. Stable in solution.
Dibromochloropropane	2.09(14°C)	11,000	1.0(21°C)	3.11x10 ⁻⁴	2.29-2.43	0.97	7.0	Stable in neutral and basic media. Reacts with dilute inorganic bases. Hydrolyzed under basic conditions to 2-bromoallyl acid. Not persistent in soil to extent that it is an accumulation problem. Light can cause free radical elimination to form chloro and bromo olefins.
1,1-Dichloroethane	1.18(20°C)	5,500(20°C)	180(20°C)	4.31x10 ⁻³	1.79	0.30	2.9	Can react with oxidizing materials.
1,2-Dichloroethane	1.25(20°C)	8,600(20°C)	64(20°C)	9.8x10 ⁻⁴	1.45-1.79	0.061	1.4	Not Documented. ³
1,1-Dichloroethylene	1.22(20°C)	2,200(20°C)	600(20°C)	3.4x10 ⁻²	1.84	0.40	3.5	Gradually decomposed by air, light and moisture to form HCl. Somewhat persistent.
1,2-Dichloroethylene	1.26(20°C)	6,300(20°C)	265(20°C)	7.6x10 ⁻³	1.48-1.53	0.16	2.0	Gradually decomposes by air, light and moisture to form HCl. Somewhat persistent.
Dicyclopentadiene	0.98	19.4	1.7(20°C)	1.9x10 ⁻²	3.14	3.80	24	-

Table 4.2 Physiochemical Properties of Select RMA Contaminants
(Page 3 of 5)

Analyte	Specific Gravity (g/ml)	Solubility (mg/l)	Vapor Pressure (mm Hg)	Henry's Constant (H _c) (atm-m ³ /mol)	Log Octanol-Water Partition Coefficient	Retardation Factor ¹	Environment Fate ²
Dieldrin	1.75	.084	1.78x10 ⁻⁷	4.6x10 ⁻⁷	3.5-6.2	27.0	168 Decomposition product of Aldrin. Very persistent in soils. Half life = 7 years. Stable to normal temperatures and to light. Hydrolysis is slow, moderate bioaccumulation.
Diisopropylmethyl phosphonate	0.98	720	0.28(25°C)	1.9x10 ⁻⁴	1.73-1.82	0.46	3.8 Half life is approximately 530 years.
Dithiane	-	3,000	0.80	-	0.77	0.087	1.5 Not documented. ³
Dimethyldisulfide	1.1	360	15	5.1x10 ⁻³	1.8	0.47	3.9 Microbial degradation, probably rapidly degraded.
Dimethylmethyl phosphonate	1.14	8x10 ⁵	.73(25°C)	-	-1.88	0.00038	1.0 Not Listed.
Endrin	1.7(25°C)	.082	2.0x10 ⁻⁷ (25°C)	1.4x10 ⁻⁶	3.5-5.6	28.0	174 Half life in soils 4 to 8 years. Rapidly transformed by sunlight to form a ketone.
Ethylbenzene	0.87(20°C)	150(20°C)	7(25.9°C)	6.4x10 ⁻³	3.1-3.2	2.15	14 Half life less than 1 month. Biodegradation somewhat persistent.
Isodrin	1.6	.17	1.0x10 ⁻⁴	33x10 ⁻⁴	4.4-6.5	145	898 Half life in soil approximately 6 years. Byproduct in an aerobic environment is endrin. Photodrin is a probable byproduct of photolysis in the environment.

Table 4.2 Physiochemical Properties of Select RMA Contaminants
(Page 4 of 5)

Analyte	Specific Gravity (g/ml)	Solubility (mg/l)	Vapor Pressure (mm Hg)	Henry's Constant (H _c) (atm-m ³ /mol)	Log Octanol-Water Partition Coefficient	Retardation Factor ¹	Environment Fate ²
Methylene Chloride	1.33(20°C)	18,000(20°C)	362(20°C)	2.03x10 ⁻³	1.25-1.30	0.061	1.4 Not Documented. ³
Methylisobutyl ketone	0.798(20°C)	19,000	16(20°C)	1.1x10 ⁻⁴	1.25	0.015	1.1 Rapidly degraded by soil micro-organisms. Half life <1 month.
Oxathiane	1.1	20,000	5.1	-	-0.16	0.019	1.1 Not Documented. ³
Dichlorodiphenylethane (DDE)	1.6	.08	6.5x10 ⁻⁶ (20°C)	6.8x10 ⁻⁵	4.86-7.1	350	2165 First decomposition product of DDT in soils. Persistent to biodegradation.
Dichlorodiphenyl-trichloroethane (DDT)	1.56	.002	5.5x10 ⁻⁶ (25°C)	5.1x10 ⁻⁴	3.98-7.48	1150	7112 Persistent in soil.
Tetrachloroethylene	1.63	2.52(20°C)	18(20°C)	2.6x10 ⁻²	2.53-2.60	1.38	10 Stable in the environment.
Toluene	0.87(20°C)	520	28(20°C)	6.4x10 ⁻³	2.6-2.7	1.64	11 Rapid degradation by microorganisms. Biodegradation. Somewhat persistent.
1,1,1-Trichloroethane	1.34(20°C)	2,500(20°C)	123(20°C)	0.0144	2.47-2.50	0.80	5.0 Biodegradation-persistent.
1,1,2-Trichloroethane	1.44(20°C)	4,500(20°C)	30(20°C)	1.17x10 ⁻³	2.47	0.65	- Microbiologically degraded, highly persistent.
Trichloroethylene	1.46(20°C)	950	58(20°C)	9.1x10 ⁻³	2.29-3.30	1.65	11 Evidence of bioaccumulation. Stable in environment. Degrades to vinyl chloride under anaerobic conditions and proper microbes.

Table 4.2 Physiochemical Properties of Select RMA Contaminants
(Page 5 of 5)

Analyte	Specific Gravity (g/ml)	Solubility (mg/l)	Vapor Pressure (mm Hg)	Henry's Constant (H _c) (atm-m ³ /mol)	Log Octanol-Water Partition Coefficient	Distribution Coefficient	Retardation Factor ¹	Environment Fate ²
Meta-xylene	0.86	130(25°C)	10(25°C)	5.6x10 ⁻⁴	3.2	4.00	26	Degraded by microorganisms. Biodegradation. Somewhat persistent.
Ortho- & Para-xylenes ⁴	0.86	180(25°C)	10(25°C)	5.6x10 ⁻⁴	2.8-3.1	4.00	26	Degraded by microorganisms. Biodegradation. Somewhat persistent.

1 Based on 30% porosity, density = 2.7 g/cm³

2 From the Chemical Index, Ebasco, 1988

3 Other than parameters listed on table

4 Average from ortho-xylene and para-xylene values

Vapor pressure is described as the ability of dissolved contaminants to volatilize from the liquid phase to the vapor phase. The Henry's Law Constant (H_c) for a specific contaminant relates the equilibrium concentration of the contaminant in liquid phase to the equilibrium concentration in vapor phase. The constant is used to predict the loss of volatile components from groundwater. As shown in Table 4.2, H_c varies for contaminants in RMA groundwater. Compounds with $H_c < 10^{-7}$ atmospheres-cubic meter per mole ($\text{atm-m}^3/\text{mole}$) are not volatile and include dieldrin. Semivolatile compounds exhibit H_c from 10^{-7} to 10^{-3} $\text{atm-m}^3/\text{mole}$, and include the organochlorine pesticides, DBCP, diisopropylmethyl phosphonate, and some of the halogenated hydrocarbons and aromatics. Volatile compounds exhibit $H_c > 10^{-3}$ $\text{atm-m}^3/\text{mole}$, and include many halogenated organics and halogenated aromatics (ESE, 1988d, RIC#88344R01).

Distribution coefficients (K_d) for RMA (Table 4.2) contaminants describe the ratio of contaminant concentration adsorbed by aquifer material to contaminant concentration in the liquid phase. Values of K_d were derived from the Task 35 Toxicity Assessment Report (Ebasco, 1987 RIC#87197R05). In addition, Task 23 (ESE, 1988d, RIC#88344R01) measured site-specific values of K_d for key RMA contaminants. The measurements consisted of comparing contaminant mass in drill cores with contaminant concentration of water samples obtained from the cored wells. This program concluded that, for organic contaminants, partitioning was primarily controlled by the concentration of organic matter in the aquifer material, and that measured values, when available, generally fell within the range of K_d values present in the literature. However, the range of K_d values present in the literature for key RMA contaminants varies over 2 to 4 orders of magnitude.

Laboratory and field experiments designed to measure the retardation factor of trichloroethylene have been conducted in the Unconfined Flow System in the Western Tier (Douglas M. Mackay, UCLA School of Public Health, written communication, 1988). Laboratory experiments consisted of column studies to estimate hydraulic conductivity and distribution coefficients as functions of depth. The field experiment consisted of a two-well recirculating test with several additional monitoring wells. Results of laboratory experiments indicated that spatial variability of aquifer properties is substantial. This suggests that field tests should be as large in scale as feasible. Results of the field experiment indicated that the retardation factor for trichloroethylene varied spatially between 1.0 and 1.8. This value is approximately an order of magnitude less than the value reported in Table 4.2.

Using a porosity of 30 percent and a bulk density of 2.7, retardation factors of the different constituents for migration within the alluvium have been calculated (Table 4.2). Given the uncertainty of K_d values, these values must be used only in a relative sense. Compounds with lower retardation factors are likely to migrate more quickly than compounds with higher retardation factors.

Organochlorine Pesticides

This group of compounds is generally persistent in soil environments and exists in waters at relatively low concentrations. Distribution in the environment is a result of relatively low aqueous solubilities, a high affinity for soil organic matter and low volatility. Therefore organochlorine pesticides which have been disposed as solid wastes in unsaturated zone soils, or in waste waters, would strongly partition to organic matter in unsaturated zone soils and would only be leached from these soils at very low rates. Once mobilized there is a tendency to remove these compounds from groundwater onto soil organic matter.

Organochlorine pesticides generally were introduced to disposal basins in solution with volatile halogenated organics. As a result, distribution coefficients calculated for organochlorine pesticides dissolved in water (Table 4.2), may not adequately describe rates of contaminant migration and retardation. In groundwater with large concentrations of volatile halogenated organics the effect of cosolvency may enhance migration of organochlorine pesticides.

Dibromochloropropane

This compound has a relatively high aqueous solubility, 1,230 mg/l, moderate volatility and a moderate affinity for organic matter in soil. Therefore dibromochloropropane (DBCP) would be solubilized at moderate rates and also lost from near surface soils by volatilization; therefore, detectable concentrations in shallow soil horizons would only be present within short periods of time following disposal. Once flushed from shallow soils DBCP will be moderately retained by soil organic matter and transported at moderate rates by groundwater.

Dicyclopentadiene

Dicyclopentadiene has a moderate aqueous solubility of 20 mg/l and moderate to high vapor pressure with a high affinity for solid organic matter. Therefore dicyclopentadiene is readily volatilized from shallow soils and surface waters. Dicyclopentadiene is also volatilized from groundwater but at lower rates due to lower temperatures encountered in this media. Transport of dicyclopentadiene in aqueous media is slower than transport of many organic compounds at RMA because dicyclopentadiene sorbs readily to organic matter.

Diisopropylmethyl phosphonate

Diisopropylmethyl phosphonate has a high aqueous solubility, 1,500 mg/l, a relatively low vapor pressure and low affinity for solid organic matter. Therefore diisopropylmethyl phosphonate is readily solubilized to surface water and groundwater and once solubilized is transported at relatively high rates due to low affinity for aquifer materials.

Organosulfur Compounds

This group of compounds has solubilities ranging from 16 mg/l to approximately 1,000 mg/l, relatively low vapor pressures, and a low affinity for soil organic matter. However, chlorophenyl-methyl sulfide has a moderately high affinity for organic matter. Therefore, organosulfur compounds will not be readily volatilized but will be dissolved and transported in surface waters and groundwaters at relatively rapid rates.

Dithiane/Oxathiane

Both of these compounds, resulting from the degradation of mustard, have high aqueous solubilities, moderate to low vapor pressures, and a low affinity for organic matter. Therefore, these compounds would readily mobilize to surface waters and groundwaters and be transported with low attenuation rates.

Volatile Halogenated Organics

All of these compounds have high aqueous solubilities, high vapor pressures, and moderate to high affinities for organic matter. Therefore these chlorinated "solvent" compounds are readily mobilized from shallow soils by vaporization and infiltration. Once in a dissolved state in surface waters and groundwaters these compounds are transported at moderate rates with moderate rates of attenuation and high rates of vaporization to the unsaturated zone.

Volatile Organics

This group of compounds is characterized by moderate to high aqueous solubilities, 100-2,000 mg/l, moderate vapor pressures, and a variable affinity for organic matter. Solubilities generally are lower than for volatile halogenated organic compounds but still high enough to result in significant losses from shallow soils due to vaporization and dissolution during infiltration.

Arsenic

This element is relatively volatile in comparison to other metals, but still would vaporize from near surface soils only at very low rates. Arsenic solubility is dependent upon Eh-pH conditions in soil-water systems but in general is more mobile than other metals due to the formation of oxyanion complexes.

Mercury

This element has high volatility relative to other metals, is readily soluble in aqueous solutions and also complexes strongly with both inorganic and organic species to form mobile complexes. Therefore, with respect to other metals, mercury is considered mobile in the environment.

Metals

The group of ICP metals (Cu, Pb, Zn, Cr, Cd) examined during the RMA Remedial Investigation are in general relatively immobile in soil environments due to the fact that these metals are not volatilized and are not readily soluble at neutral to basic pH values. Solubility is dependent upon specific Eh/pH conditions of the soil/water system, but at RMA these metals are strongly retained in unsaturated zone soils.

4.4.2 Attenuation of Target Analytes

During the process of contaminant transport a number of physical and chemical processes occur which result in a reduction of the measured concentration of a target analyte. The processes which most strongly affect reductions in contaminant concentrations include degradation (hydrolysis, photolysis and biodegradation), sorption, and volatilization. Each of these processes is discussed in more detail below.

Sorption

Partitioning between coexisting aqueous and solid phases is a critical factor in determining the extent to which a contaminant will be transported in groundwater. Contaminants that are strongly adsorbed, having an affinity for organic matter and fine-grained mineral and clay surfaces, will not migrate significantly from the place where they are introduced. For strongly adsorbing chemicals, erosion and surface runoff of contaminated soil particles may provide a significant migration pathway. Chemicals that are weakly adsorbed, having an affinity for the dissolved aqueous phase, will be readily leached from contaminated soil and move with groundwater. Many contaminants of concern are moderately adsorbed and exist in both solid and aqueous phase. The degree to which a compound is adsorbed to naturally occurring organic carbon is directly related to the magnitude of the octanol-water partition coefficient (K_{ow}) for the compound.

Volatilization

Volatilization is the process by which a compound evaporates from either a liquid or solid phase to the gas phase. Loss of contaminants by volatilization can be substantial in soil and can decrease contaminant mass available for migration with water. The degree to which a compound will be volatilized depends on physical and chemical characteristics, such as vapor pressure and Henry's Law Constant, as well as properties of the soil or water phase.

Transformation and Degradation

Transformation and degradation processes determine if a chemical will persist in the environment. Transformation and degradation of contaminants generally result in reaction products that are less hazardous. However, results of these processes can be of greater concern due to increased toxicity, persistence, or mobility. Rates at which these processes occur depend on individual chemical, soil, and environmental characteristics. In general the processes occur at faster rates in the surface environment than in the subsurface. A chemical that is buried will tend to degrade more slowly than the same chemical exposed at the soil surface.

Key transformation processes are biotransformation, hydrolysis, photolysis, and oxidation-reduction. During hydrolysis, an organic compound reacts with water resulting in the addition of a hydroxyl group to the molecule and elimination of another functional group. Transformation by photolysis can occur by absorption of solar radiation or by deriving

energy from another species in solution. Inorganic oxidation and reduction results in the loss of electrons by one chemical and the gain of electrons by another. Organic oxidation reactions generally result in a gain of oxygen and loss of hydrogen while the reverse generally is true for organic reduction. Oxidation and reduction often are biologically mediated. Biotransformation occurs as a result of metabolic activity of microorganisms that use enzymes to catalyze chemical reactions.

4.5 Contaminant Source Areas and Pathways

Previous investigations at RMA have documented sources of water contamination. The interpretive work performed in support of Section 4.0 of this report confirms five major source areas that contribute to water contamination at RMA. These areas are the South Plants Manufacturing Complex, Basin A, Basin F, North Plants Manufacturing Complex and the Western Tier sites (Figure 4.2). The chemical sewer system has also been identified as a source of contamination. In addition to major source areas, suspected source areas have been identified when the source of contamination is masked by the presence of a major source area along the contaminant pathway. Suspected source areas include the Western Tier Warehouse Area, Lake Mary Overflow, Sand Creek Lateral, and Basins B, C, D, and E.

Primary groundwater pathways away from each source area noted above are flow paths which exhibit pervasive and historically frequent occurrences of one or more RMA contaminants (Figure 3.1). Surface water pathways include ponds, ditches, canals, and natural drainages where contaminants have been detected or where the migration of contaminants with surface water is probable. The sewer systems and process water systems at RMA have also contributed to contaminant migration. Surface water, groundwater, and sewer or process water pathways for each major source area are described below.

4.5.1 South Plants Source Area and Pathways

The South Plants Manufacturing Complex was constructed in 1942 with various structures and facilities added at later dates. Sewers within South Plants were constructed in 1942 and were upgraded and expanded through time. Various chemical and incendiary munitions were manufactured at this complex. Chemicals manufactured during 1943 included mustard,

lewisite, acetylene, arsenic trichloride, sulfur monochloride and dichloride, thionyl trichloride, chlorine and caustic. In addition, various incendiary weapons were manufactured at the complex during this timeframe. Between 1943 and 1948 distilled mustard operations took place. These operations included mustard distillation and shell/ton container filling. Army operations at South Plants during the 1950s, '60s and '70s included the manufacture and filling of incendiary weapons. In addition various demilitarization activities were undertaken. Continuous Army operations in the South Plants Area include clothing impregnation and analytical laboratory activities.

Various facilities within the South Plants Manufacturing Complex were leased to private industry for the manufacture of chemicals from 1946 to 1982. Manufactured chemicals include chlorinated insecticides, organophosphate insecticides, carbamate insecticides, herbicides and soil fumigants. Additional information on the specific time that these chemicals were manufactured can be found in the South Plants Study Area Report and the Remedial Investigation Contamination Assessment Reports pertaining to South Plants.

Many of the compounds on the target list have been detected in South Plants; however, the most commonly occurring contaminants in soils are organochlorine pesticides, arsenic, mercury, volatile halogenated organics, volatile aromatics, and volatile hydrocarbons. Although relatively low levels of contaminants are present throughout most of the South Plants, the most concentrated areas of contamination are the central processing area and South Tank Farm located in the north-central and southeastern portions of the complex respectively. Organochlorine pesticides, arsenic, mercury, volatile halogenated organics, volatile aromatic organics, and DBCP are common in the soils in the central processing area. Benzene and other volatile aromatic organics and volatile hydrocarbons are common in the area of the South Tank Farm.

Several analyte groups including organochlorine pesticides, organosulfur compounds, volatile hydrocarbons, volatile aromatic organics, and volatile halogenated organics have been detected in surface water collected from ditches which exit the South Plants. Historically, discharges from pipelines and the direct flow of chemicals to ditches during spill events was likely. Under current conditions, runoff may erode contaminated soils and transport and deposit them in downstream areas. Contaminants may also be dissolved by surface water and later deposited elsewhere. Contaminated surface water and potentially contaminated sediments are transported from South Plants north into Basin A,

southeast into Lower Derby Lake and west to Sand Creek Lateral. Contaminated soils and surface water are present in Basin A and are described later. Water in the Lower Lakes is not considered to be contaminated, however, pesticides and mercury have been detected in the lake bottom sediments. Sand Creek Lateral flows north towards Section 26 and is a suspected source of groundwater contamination in Section 35. Surface water may also be retained in the processed water cooling pond or isolated closed depressions. This stored surface water may infiltrate downward to the water table.

Numerous contaminants have been detected in groundwater beneath South Plants including organochlorine pesticides, organosulfur compounds, volatile halogenated organics, volatile aromatic organics and other organic compounds such as dicyclopentadiene, diisopropylmethyl phosphonate, acetone, bicycloheptadiene and methylisobutyl ketone. The depth to groundwater varies from approximately 5 to 10 feet in the central portion to 35 feet in the northwest and south portions of the area.

A variety of activities have resulted in the deterioration of groundwater quality in the area. The primary site-specific mechanisms by which contaminants may have been introduced into the groundwater at South Plants are summarized in Table 4.3.

Throughout most of RMA, plumes flow away from their given source areas in a single direction. However, groundwater and contaminants flow away from the central portion of the South Plants in several directions (Figure 3.1). Four preferential flow paths for contaminant migration that radiate away from the mound have been identified in the South Plants Study Area Report as the north, southeast, south and west-southwest flow paths. The north flowpath is the widest and contains the most analytes. The southeast flow path contains fewer analytes than the north flow path and is commonly distinguished by two areas of higher concentration connected by an area of lower concentration. The northwest flow path is less well defined and has fewer contaminants than the north or southeast flow paths. The south flow path contains continuous plumes of volatile halogenated organics and volatile aromatic organics (Appendix F, Figures 4.2-9 and 4.2-14). This flowpath continues through the South Tank Farm area and extends southwestward toward Lake Ladora. The west-southwest flowpath contains only carbon tetrachloride and chloroform (Appendix F, Figure 4.2-15). Maximum concentrations are much lower within

Table 4.3 Mechanisms for the Introduction of Contaminants to Groundwater

Condition	South Plants	Basin A	Basin F/ Other Basins	North Plants	Western Tier	Sand Creek Lateral
Accidental Release associated with Building Operation, includes spills, leaking pipelines, sumps and defective equipment	X			X		
Building basement intersecting the groundwater resulting in entry of contaminated groundwater and/or mixing of spills with groundwater	X					
Spills associated with tank or tank car filling operations	X	X		X	X	
Underground storage tank leaks or groundwater intersection with the tank	X			X	X	
Leaking sewer lines or intersection of sewer with groundwater	X	X	X	X		X
Disposal pits, lime basins, or decontamination basin remobilization of a contaminant via surface water or groundwater, or both	X	X				
Historic and seasonal water table variations	X	X	X			
Ditches either transport contaminated runoff or intersect the groundwater	X	X	X	X	X	X
Vertical migration of contaminants via an improperly constructed or abandoned well or conducive geologic conditions, i.e. highly fractured bedrock or material with a large hydraulic conductivity in contact with a paleochannel	X	X	X			
Open storage yards improper decontamination of equipment	X	X		X		

this flowpath than along other South Plants flowpaths. Additionally, a plume of diisopropylmethyl phosphonate and dicyclopentadiene extends southwest from the Steam/Chlorine Plant.

4.5.2 Basin A Source Area and Pathways

Basin A, an unlined basin, was used beginning in 1943 for the disposal of contaminated wastes from South Plants. Beginning in 1953 wastes from North Plants were also disposed in the basin. The additional waste added to Basin A from North Plants resulted in it being filled to capacity. A new lined disposal basin, Basin F, was constructed to replace Basin A. The ponded liquid wastes contained in Basin A were transferred to Basin F between December 1956 and September 1957. With the exception of the period May 1 to June 2, 1957, Basin A was not used for liquid waste disposal after December 1956. The Army continued to drain accumulated surface run-off in Basin A to Basin F until the summer of 1960.

A large variety of contaminants at elevated concentrations have been detected in Basin A soils. The most commonly occurring compounds include organochlorine pesticides (primarily dieldrin), mercury, arsenic, and diisopropylmethyl phosphonate.

Surface runoff from the northern portion of South Plants and surrounding areas collects within topographic depressions contained within Basin A. Numerous contaminants including volatile halogenated organics, volatile aromatic organics, volatile hydrocarbons, organochlorine pesticides, organosulfur compounds, DBCP and arsenic have been detected in Basin A surface water. Surface water can discharge from Basin A to Basin B via a northwest trending ditch. A ditch located west of the basin also carries surface water from South Plants along the western margin of Basin A and eventually discharges to Section 34. This ditch has been breached in some areas and surface flow can overflow and collect in Basin A. More target analytes have been detected in this ditch than in the central pool of Basin A, but generally at lower concentrations.

Groundwater contaminants that occur in the greatest concentrations in the vicinity of Basin A include dithiane/oxathiane, benzene, chlorobenzene, chloroform, diisopropylmethyl phosphonate, fluoride, and chloride. Other target analytes have also been detected, but at lower concentrations. The highest concentrations of most contaminants are located in the

southwestern corner of Section 36. The source of contaminants probably was nearby disposal pits and/or leaky sewer lines. Compounds such as benzothiazole, dicyclopentadiene, diisopropylmethyl phosphonate, arsenic, fluoride, and chloride are most concentrated in the northern portion of Basin A. Groundwater is generally within a few feet of the surface and may locally recharge the surface ponds within Basin A.

The primary pathway from the Basin A source area is the Basin A pathway. This pathway originates in the southern portion of Section 36 and continues through a northwest trending paleochannel known as Basin A Neck. Most of the contaminants detected in the Basin A source area have also been detected in the Basin A Neck pathway. Contaminants have also been detected in unconfined portions of the Denver Formation beneath unsaturated alluvium along the northern margin of Basin A. In addition, zone A of the Denver Formation subcrops on either side of the Basin A Neck paleochannel and intersects with alluvial materials. These conditions indicate that lateral migration of contaminants northward through the Denver Formation may be occurring.

4.5.3 Basin F Source Area and Pathways

Basin F, a 92.7 acre disposal pond equipped with a catalytically blown asphalt liner and 12 inch protective earthen blanket, was built by the Army between July and December 1956. Basin F had a capacity of 240,000,000 gallons and was built to contain contaminated waste from Army and lessee (principally Shell) chemical operations. The basin was constructed on the site of a large natural depression. Eight and 10 inch underground gravity flow vitrified clay sewer laterals were installed, linking Basin F to chemical sewer lines from the Chlorine Plant, the Shell manufacturing area in the South Plants, and the North Plants complex. By December 1956, final work on dikes and connecting sewer laterals was complete and all contaminated liquid waste was being discharged to Basin F. Basin F was used continuously between 1956 and 1981 for the solar evaporation of contaminated aqueous wastes.

Nearly 100 hazardous chemicals are known to have been present in liquid waste discharged to Basin F. In very limited areas of Basin F organochlorine pesticides, DBCP, dicyclopentadiene, volatile halogenated organics, and volatile aromatic compounds were detected in soils at depths of 20 ft or greater. In some areas in the eastern side of the basin where the liner appeared to be deteriorated, there is a relatively uniform vertical

distribution of organic compounds. This suggests that downward fluid migration has occurred over a long time period and that maximum soil retention of these compounds has been attained in the soil column down to the water table in these limited areas.

Surface water was diverted around Basin F and inlets were blocked so that direct precipitation was the only source of inflow to the basin. No surface outflows of surface water or contaminated wastes occurred at the basin.

Many compounds have been detected in groundwater in the Basin F area. Downgradient wells immediately northeast of Basin F have greater frequency and concentrations of contaminants, notably DBCP, diisopropylmethyl phosphonate, dithiane, chlorophenylmethyl sulfone and volatile aromatic compounds, than other adjacent wells. Contaminant occurrences and concentrations upgradient of Basin F are variable. Wells south of Basin F in the vicinity of Basin C generally contain numerous contaminants, whereas wells to the southeast generally contain fewer contaminants at lower concentrations. The depth to groundwater below land surface ranges from approximately 35 to 45 ft.

The primary mechanisms by which contaminants were introduced in the groundwater at Basin F are summarized in Table 4.3. Leakage of Basin F fluids through damaged portions of the liner and from sewers with downward infiltration through the vadose zone are the most important mechanisms in the Basin F area.

The Basin F contaminant pathway which trends from Basin F to the North Boundary Containment System. Diisopropylmethyl phosphonate, oxathiane/dithiane, organosulfur compounds, dicyclopentadiene, benzene, tetrachloroethylene, trichloroethylene, fluoride, chloride, and arsenic all exclusively follow the primary Basin F pathway. DBCP and endrin follow a second Basin F pathway located east of and parallel to the first Basin F pathway. Other compounds such as dieldrin and chloroform occur in both pathways. Many volatile halogenated organics and volatile aromatic organics occur in the Basin F east pathway which originates south of Basin F. Dieldrin, diisopropylmethyl phosphonate, arsenic, chloride and fluoride occur in the Basin F west and northwest pathways that trend from Basin F to the northwest boundary of RMA.

4.5.4 North Plants Source Area and Pathway

The North Plants Manufacturing Complex was in operation between 1953 and 1969. Operations in this facility included the manufacture of the nerve gas GB (Sarin) and associated munition filling. Compounds used in the manufacture of GB include methylphosphonic dichloride (dichlor), hydrofluoric acid, isopropyl alcohol and tributyl amine. In addition to the above operations various demilitarization of various items occurred between 1965 and 1984. These demilitarization operations included munitions filled with GB, phosgene and other agent-containing munitions. Solvents used at the facility include carbon tetrachloride and 1,1,1-trichlorethane.

Fewer and generally lower concentrations of compounds were detected in North Plants than in the South Plants, Basin A and Basin F source areas. The most notable compounds in the North Plants soils are volatile halogenated organics, arsenic, mercury, dimethylmethyl phosphonate, chloroacetic and dieldrin.

Ditches which may carry surface water from the North Plants to First Creek are normally dry. However, contaminant migration along these ditches could occur during storm events for short time periods. The depth to groundwater in the North Plants area is approximately 25 feet.

Diisopropylmethyl phosphonate is the primary contaminant observed in the North Plants area. However, low levels of volatile halogenated organics, mainly chloroform, as well as mercury and fluoride have also been detected. The primary mechanisms by which contaminants were introduced into the groundwater at North Plants are summarized in Table 4.3.

The North Plants pathway originates in North Plants and trends toward the north boundary of RMA. The primary contaminant detected in this pathway is diisopropylmethyl phosphonate. Several wells have recently been installed in this pathway to better characterize the nature and extent of contamination in this area.

4.5.5 Western Tier Source Areas and Pathways

Two building complexes, the Rail Classification Yard and the Western Tier Motor Pool Area are source areas in the Western Tier.

The Rail Classification Yard was used to store a variety of tank cars which contained various chemicals. This area has been identified as the source of DBCP contamination detected in the off-post community of Irondale in 1980. The Irondale Containment/Treatment System was constructed to control off-post migration of this contaminant.

The Western Tier Motor Pool Area was constructed in 1942. The area was used for support operations. Located within the Motor Pool is an area where solvents were used for degreasing operations.

Sporadic occurrences of volatile organic compounds, mainly solvent related, and pesticides were detected in the Railyard and Motor Pool areas. Other sites located west or north of the Motor Pool also contain isolated contaminants, but do not appear to be sources of groundwater contamination. In general, the amounts of contamination in the Western Tier are much lower than other source areas such as South Plants or Basin A.

The potential for the migration of contaminants in surface water is limited. Most surface water collects in short ditches or closed depressions where much is lost to evaporation. However, it is likely that surface contaminants are carried to and accumulate in the topographic low areas. Some surface water will infiltrate the vadose zone and discharge soluble contaminants to the Unconfined Flow System.

The main contaminants in the Western Tier groundwater are volatile halogenated organics, volatile aromatics and DBCP. The depth to groundwater in the source areas of the Western Tier is approximately 60 feet. Therefore, direct discharges of contaminants to the groundwater are not possible. The primary site specific mechanisms by which contaminants were introduced into the groundwater in the Western Tier are summarized in Table 4.3.

Three general groundwater migration pathways have been identified as the off-post Western Tier, Western Tier, and Motor Pool and Railyard pathways. Volatile halogenated organic plumes consisting mainly of trichloroethylene and DBCP are present in these Unconfined Flow System flowpaths. The off-post Western Tier plume flows from an off-post source located southwest of RMA north to the South Adams County Water and Sanitation District water supply wells. The Western Tier plume flows north from an off-post source located south of RMA. A third trichloroethylene plume flows from the Motor Pool area towards the Irondale Containment System. These plumes are best defined by concentrations of trichloroethylene, but other volatile halogenated and aromatic organics have been detected across the area in broader and less distinct trends. A DBCP plume originates in the Railyard in Section 3 and follows a pathway that is parallel to and east of the trichloroethylene plume that originates in the nearby Motor Pool. This DBCP plume is captured by the Irondale Containment System.

4.5.6 Chemical Sewer

The chemical sewer is a gravity system that collected chemical wastes from manufacturing activities at RMA and transported them to Basin A, and later to Basin F. The first chemical sewer was installed in the South Plants Manufacturing complex in 1942. It originally consisted of three separate waste systems; the toxic waste system, the nontoxic contaminated waste system, and the caustic waste system. These systems were consolidated in 1956 and all chemical wastes were then routed to Basin F.

The North Plants chemical sewer was built by the Army in 1952 during initial construction of the North Plants complex. This system included a collection system leading to the contaminated waste sump (building 1727), and trunk lines leading from the sump to Basin A.

The South Plants and North Plants chemical sewers were linked in 1956 when an interceptor line was constructed. This line originated in South Plants and headed north to collect wastes from North Plants before emptying into Basin F. The chemical sewer interceptor line was removed by the Army in 1982 and the collection systems in both North and South Plants were abandoned in place.

The chemical sewer in South Plants was constructed of vitrified clay pipe with brick manholes. Chemicals transported by the chemical sewer caused extensive deterioration of this system, and leakage was known to occur. These problems were complicated by the high water table in the South Plants area. Some segments of the sewer were in direct contact with groundwater and any leaks in the system could become direct sources of these chemicals to the groundwater.

The chemical sewer collection system in North Plants was constructed of cast iron and is assumed not to have deteriorated nearly as much as the South Plants system. The portion of the line downstream of the sump (Building 1727) was constructed of vitrified clay pipe. This was investigated in the Remedial Investigation and no significant contamination was identified (Ebasco, 1988d).

4.5.7 Other Source Areas and Pathways

In addition to the five major source areas described previously, other areas have been identified as suspected source areas. These source areas have been identified by historical information describing the presence of the chemical in the area and/or a contaminant plume being present either at the site or downgradient of the site. Areas which fall under this category include the Sand Creek Lateral and Basins B, C, D, and E.

Sand Creek Lateral

Sand Creek Lateral was present in the 1940s prior to the construction of RMA. The canal was used for irrigation. During the 1940s and early 1950s the canal was used intermittently to transport chemical waste from the South Plants area to disposal basins located to the north. Because the overall gradient of the lateral is low, much of the water would not reach the basins, but would pond and either infiltrate or evaporate.

The Central North, Central South, and the Basin A Neck pathways extend from the Sand Creek Lateral towards the northwest boundary of RMA. Dieldrin and chloroform have been detected along the Central North and Central South pathways. Numerous contaminants have been detected in the Basin A Neck pathway which is described in the Basin A source area discussion above.

Basins B, C, D, and E

Basins B, C, D, and E were used in the early 1950s for chemical waste disposal prior to the construction of Basin F. Overflow from Basin A could eventually enter these basins. Basin B would first receive the overflow and when the basin filled flow could be diverted to the other basins. Prior to the dam in Basin A being raised 5 feet in the early 1950's liquid wastes from Basin A overflowed into Basin B.

Basin C held water during 1957 and 1958, again in 1966 and 1967 and, for a third time during the consecutive years beginning in 1969 and ending in 1974. Liquid wastes were transferred from Basin F to Basin C on one occasion only in the spring of 1957 and were retained in Basin C for a period of approximately 30 days while the liner in Basin F was repaired. The liner was damaged due to wind induced wave action.

Basins D and E received liquid wastes discharged via the Sand Creek Lateral (1942-1953), liquid waste overflows from Basins B and A (1946-1953) and overflows from Basin C (1953-1956). Despite the modifications to the Basin A dam in 1951 and again in 1952, liquid waste overflows from Basin A continued. Overflow discharges from Basin A flowed to Basin B and ultimately to Basins D and E.

The continuation of the Basin A Neck pathway is the primary pathway away from the Basins Area. In addition, some migration may presently be migrating, or may have historically migrated, from Basin C northward along the Basin F east pathway.

Other Pathways

The Northern Off-Post and First Creek Off-Post pathways originate at the North Boundary Containment System and extend off-post to the north and northwest, respectively. Contaminants which are commonly detected include chloroform, dicyclopentadiene, DBCP, diisopropylmethyl phosphonate, tetrachloroethylene, organosulfur compounds, and dieldrin.

The Quincy Street Pathway extends from the Northwest Boundary Containment System towards the northwest. Dieldrin, chlorobenzene, and chloroform plumes extend off-post along this pathway.

4.6 Contaminant Migration and Alteration Along Major Groundwater Pathways

The purpose of this section of the report is to describe hydraulic characteristics, rates of contaminant migration and mechanisms for alteration of contaminants along major groundwater pathways. Based on the description of hydraulic characteristics and the potentiometric surface configuration for the Third quarter of FY1987, rates of advective transport and apparent times of migration are estimated for each pathway. Where possible, results of these estimates are compared to maps showing the distribution of contaminants and reasons for any differences are noted. An evaluation of adsorption-desorption is made by comparing contaminant distribution maps for consistency with partition coefficients (K_d). Possible reasons for any inconsistencies are noted.

Major pathways were identified previously in Section 4.5. Although the emphasis of pathway identification and discussion is placed on flow in the Unconfined Flow System, flow in the Denver aquifer will be discussed in areas where substantial migration has been noted. Major pathways discussed in this section of the report are South Plants, Basin A-Basin A Neck, Central, Basin F and Western Tier. Discussions of off-post contamination are included in the Off-Post Operable Unit Remedial Investigation and Chemical Applicable or Relevant and Appropriate Requirements, Draft Final Report (ESE, 1989b, RIC#89024R01).

4.6.1 South Plants Pathways

Contaminant migration from the South Plants area occurs along several pathways identified in Section 4.5. Pathways radiate from the centrally located water table mound beneath South Plants indicating that enhanced recharge has probably occurred in this area. Although several pathways originating at South Plants have been identified, migration along only two of these pathways will be described in this section of the report. One pathway causes contaminant migration north from South Plants toward Basin A. The second pathway causes migration southwest toward Lake Ladora.

Water in the north pathway flows primarily through eolian and alluvial deposits of the Unconfined Flow System. However, flow is through unconfined Denver Formation in the central part of the water table mound. Saturated thickness is less than 10 ft beneath South Plants but increases to 30 ft near Basin A (Plate 2). Estimates of hydraulic

conductivity obtained from long-term pumping tests in alluvial material near South Plants and Basin A are approximately 14 ft/d in alluvial material, and 3 ft/d in the unconfined Denver Formation (Appendix F, Section 2.0).

Average linear velocity and groundwater travel time along the north pathway have been calculated for various assumed values of effective porosity. Hydraulic gradient was obtained from Figure 2.4 and a value of 14 ft/d for alluvium and 3 ft/d for unconfined Denver Formation were used for hydraulic conductivity. Average linear velocity in alluvium ranged from 0.32 ft/d to 2.5 ft/d assuming effective porosity values from 0.05 to 0.4. Average linear velocity in unconfined Denver Formation ranged from 0.24 to 2.4 ft/d assuming effective porosity values between 0.01 and 0.10. Groundwater travel time from the center of the water table mound to the center of Basin A ranged from 4.1 years to 34 years. These estimates could not be readily compared with maps showing contaminant distribution because contamination from source areas beneath Basin A masks evidence of migration from South Plants.

Water in the southwest pathway flows primarily through unconfined Denver Formation. Consisting primarily of claystone and volcanoclastic sediments, the Denver Formation is weathered and fractured near South Plants. Saturated thickness is generally 10 to 20 ft along the pathway. Hydraulic conductivity estimated from a long term pumping test of the unconfined Denver Formation is approximately 3 ft/day. Volatile aromatic contaminants including benzene occur along the pathway.

Average linear velocity and groundwater travel time along the southwest pathway were estimated using hydraulic gradients extrapolated from Figure 2.4, hydraulic conductivity of 3 ft/d and assumed values for effective porosity that ranged from 0.01 to 0.10. Average linear velocity ranged from 0.075 ft/d to 0.75 ft/d. Groundwater travel time from the center of the water table mound to Ladora Lake ranged from 16 years to 160 years.

Water levels in the Unconfined Flow System along the southwest pathway are near the base of alluvial deposits and small increases in water levels would cause the alluvial deposits to become saturated. Water level changes as large as 7 ft have been measured beneath South Plants in the past 5 years. If alluvial deposits became saturated, average linear velocity along this pathway probably would increase substantially and groundwater travel time would decrease.

4.6.2 Basin A-Basin A Neck Pathways

Contaminant migration from source areas beneath Basin A and other source areas that are hydraulically upgradient occurs primarily in alluvial deposits from Basin A through the Basin A Neck. The bedrock composition directly underlying the alluvial deposits consists of poorly cemented subcropping sandstone and siltstone lenses that provide direct hydraulic connection between the alluvium and Denver Formation.

Water in the Basin A - Basin A Neck occurs primarily in areas of saturated alluvium and underlying unconfined parts of the Denver Formation. Saturated thickness of the Unconfined Flow System in this area typically is less than 10 ft. Hydraulic conductivity is not accurately known. Estimates range from 12 ft/d for a pumping test beneath Basin A to 280 ft/d (Figure 2.3) for a paleochannel beneath Basin A Neck. Flow model results indicate that hydraulic conductivity is approximately 10-20 ft/d in the Basin A-Basin A Neck Area (HLA, written communication, 1988).

Average linear velocity and groundwater travel time along the Basin A-Basin A Neck pathway have been calculated for various assumed values of effective porosity. Hydraulic gradient was extrapolated from Figure 2.4 and a value of 12 ft/d was used for hydraulic conductivity. For effective porosity values from 0.1 to 0.4 average linear velocity ranged from 0.36 ft/d to 1.4 ft/d. Corresponding travel times from the center of Basin A to the down-gradient end of Basin D range from 12.3 years to 49.4 years.

Basin A was used for waste disposal primarily from 1943 to 1956. Based on the assumption that dithiane and oxathiane, byproducts in the manufacture of mustard gas, were introduced to Basin A, it is reasonable to compare calculated travel time with contaminant distribution maps. Dithiane and oxathiane are relatively nonsorbing organosulfur compounds. The contaminant distribution map for dithiane and oxathiane (Appendix F, Figure 4.2-5) indicates that the contaminants have migrated to the area beneath Basin E. Assuming that Basins D and E were not major sources of these contaminants, a travel time of 44 years, average linear velocity of 1.1 ft/d, and to an effective porosity of 0.31 approximately matches the observed distance of migration.

Secondary pathways for contaminant migration through subcropping sandstone and siltstone lenses of the Denver Formation can be formed under appropriate hydrologic conditions. Two secondary pathways have been identified in the Basin A-Basin A Neck area. Although lateral migration along these pathways may occur through upper parts of the Denver Formation, small increases in water levels from present day conditions could cause groundwater flow and contaminant migration through alluvium. The water table elevation as of Third Quarter FY87 is at or just below the bedrock contact in the area north of the Basin A Neck.

Figures 3.13 through 3.17 identify areas of nearly continuous contamination by inorganic compounds, primarily fluoride and chloride, in the upper sandstone stratigraphic units of the Denver aquifer. The areas of contamination generally occur in the sandstone unit that subcrops beneath the Unconfined Flow System or the immediately underlying unit. The area of contamination extends from Basin A, through the Basin A Neck, beneath Basins C and F, and toward the northwest. The orientation of this contaminated area coincides with the direction of flow inferred from potentiometric surface maps of the Denver aquifer (Appendix F, Figures 2.4-5 through 2.4-10). Contamination may be the result of migration along relatively short flow paths originating locally in contaminated water of the Unconfined Flow System. Because migration mechanisms in the Denver aquifer are complex, average linear velocity and travel time are not calculated.

4.6.3 Central Pathways

Based on contaminant distribution in Sections 27 and 34, several pathways, collectively called the Central Pathways, have been identified. A major pathway extends from beneath Basin D to the Northwest Boundary Containment System and is a continuation of the Basin A-Basin A Neck pathway. Other pathways originate near the Sand Creek Lateral or Basin F and have been traced toward the Northwest Boundary Containment System. Contaminants along the Central Pathways occur primarily in alluvial deposits of the Unconfined Flow System.

Hydraulic characteristics of the Unconfined Flow System along the Central Pathways are similar to hydraulic characteristics within the Basin A Neck. Saturated thickness typically is 10 ft or less; however, a north-trending channel with a saturated thickness of 20 ft is located in the western part of Section 27. Hydraulic conductivity estimates from aquifer

tests near the Northwest Boundary Containment System indicate that a value of approximately 1,600 ft/d is typical for the north-trending channel in Section 27. Hydraulic gradients in areas east of this channel indicate that hydraulic conductivity is similar to the estimate in the Basin A Neck.

Average linear velocity and groundwater travel time along the Central Pathway from Basin D to the Northwest Boundary Containment System have been calculated for various assumed values of effective porosity. Hydraulic gradients were obtained from Figure 2.4. A value of 20 ft/d was used for hydraulic conductivity in the eastern part of Section 27 where gradients are relatively steep. A value of 1,600 ft/d was used for hydraulic conductivity in the area of relatively flat gradient in the western part of Section 27. For assumed values of effective porosity from 0.1 to 0.4, average linear velocity ranged from 0.5 ft/d to 2.0 ft/d in the area of steep gradient, and 16 ft/d to 64 ft/d in the area of flat gradient. Corresponding travel times from the down-gradient end of Basin D to the Northwest Boundary Containment System range from 6.7 years to 27 years.

Calculated linear velocity compares well with apparent velocities of contaminants that are slightly sorbing. Diisopropylmethyl phosphonate is associated with manufacturing of the nerve gas agent GB and was disposed in Basin A from 1953 through 1956. During 1957 wastes containing diisopropylmethyl phosphonate were stored in Basin F. However, Basin F waste was pumped into Basin C in 1957 for a period of approximately 30 days while repairs were made to the Basin F liner. Figure 3.7 shows diisopropylmethyl phosphonate plumes along two Central pathways. This pattern, along with the late 1950's configuration of the water table (Smith and others, 1963, RIC# 84324R02), indicates that the source of these plumes probably was Basin C. Based on present-day hydraulic gradients, a travel time of 29 years, average linear velocity of 1.2 ft/d, and an effective porosity of 0.25 approximately matches the observed distance of migration. If hydraulic gradients measured in the late 1950's are used, a reasonable match is obtained with an effective porosity of 0.35.

In addition to the contaminant diisopropylmethyl phosphonate, contaminant distribution of chloroform is consistent with available hydraulic information and models. Chloroform plumes in Appendix F, Figure 4.2-15 appear to be migrating away from sources either along Sand Creek Lateral or South Plants. Sand Creek Lateral was used to convey pesticide waste, including chloroform, from South Plants area to the basins between 1952

and 1964. Assuming the source of contamination was Sand Creek Lateral and contamination occurred in 1957, a travel time of 30 years and an effective porosity of 0.4 approximately matches the observed distance of migration. The observed distance of migration also can be matched by assuming the source of contamination was South Plants. A match is possible by assuming an effective porosity of approximately 0.2 for alluvium and approximately 0.05 for the unconfined Denver Formation between South Plants and Sand Creek Lateral.

4.6.4 Basin F Pathway

Contaminant migration from source areas beneath Basin C and Basin F occurs in alluvial material and weathered bedrock of the Unconfined Flow System. The Basin F Pathway extends north to the North Boundary Containment System. Saturated thickness of the Unconfined Flow System along the pathway typically is less than 10 ft. The median value of hydraulic conductivity obtained from aquifer tests near the pathway is approximately 230 ft/d. Hydraulic conductivity estimated from a single aquifer test near Basin F is 1 ft/d (Figure 2.3).

Average linear velocity and groundwater travel time along the Basin F pathway have been calculated for various assumed values of effective porosity. Hydraulic gradient, obtained from Figure 2.4, reflects present-day conditions. A value of 230 ft/d was used for hydraulic conductivity. Assuming effective-porosity values between 0.1 and 0.4, average linear velocity ranges from 1.0 ft/d to 4.0 ft/d. Travel time from the northeast corner of Basin F to the North Boundary Containment System ranges from 4.2 years to 16.8 years.

Hydraulic gradients in recent years are substantially less than gradients from 1957 to 1971. Basin C was used as an artificial recharge basin during part of this period. Hydraulic gradients from Basin C to the northern boundary of RMA from 1957 to 1971 were approximately 3 to 5 times greater than present-day gradients. Average linear velocity during periods when Basin C stored water was 3 to 5 times larger than present-day velocity. Travel time from Basin F to the northern boundary of RMA probably was 3 to 5 times shorter.

Calculated values of average linear velocity compare favorably with the rate of migration for diisopropylmethyl phosphonate (Figure 3.7). Assuming this chemical was introduced to

the groundwater system beneath Basin F in 1957, the rate of contaminant migration is approximately 2.3 ft/d. This indicates that diisopropylmethyl phosphonate is essentially nonsorbing in the alluvial materials of the Unconfined Flow System.

Near the RMA North Boundary, groundwater flows primarily through coarse basai sediments of the alluvium with substantially less flow through upper alluvial layers of relatively fine-grained eolian deposits and the fractured or weathered materials of the upper Denver Formation. Flow direction near the North Boundary Containment System is to the north. Flow through the alluvium downgradient of the North Boundary area has generally taken place along two distinct flow paths. These flow paths were primary factors that determined how contaminants migrated to off-post areas before the North Boundary Containment System was installed.

Changes in flow patterns as a result of the North Boundary Containment System have been noted within about 500 feet of the System. Water in the Unconfined Flow System has mounded on the upgradient side of the soil-bentonite barrier and the upgradient water table is up to 9 ft higher than on the downgradient side of the barrier. This condition has apparently resulted in contaminant migration beneath the pilot portion of the system. Much of the large head differences across the barrier have been attributed to inadequate North Boundary Containment System recharge capabilities downgradient of the pilot portion of the system. This situation has been addressed through installation of recharge trenches, and the hydraulic gradient has now been reversed across the North Boundary Containment System.

Near the North Boundary Containment System the Denver Formation consists of a 250 to 300 ft thick series of carbonaceous clayshales, claystones, and siltstones. These fine-grained sediments are interbedded with weakly lithified, more permeable, lenticular sandstone units. Where sandstones are uncemented, they act as the dominant pathway for lateral groundwater flow through the Denver Formation. However, in the upper Denver Formation, the low permeability strata may be heavily weathered and fractured and have hydraulic conductivity similar to that of sandstone units. The average thickness of sandstone units near the North Boundary Containment System averages from about 10 ft for crevasse-splay type deposits to over 20 ft for channel type deposits. The regional groundwater flow direction through the Denver aquifer is to the northwest. However, changes in the water table configuration caused by the North Boundary Containment

System have created more of a northward direction in the uppermost units beneath the system. Hydraulic conductivity of the Denver aquifer varies significantly near the North Boundary Containment System and ranges from about .007 ft/d to 1.6 ft/d. Average linear velocity within the most permeable zones of the Denver Formation was estimated at less than 0.03 ft/day.

The more strongly sorbed compounds in the Basin F pathway tend to occur over less extensive areas and tend to migrate over shorter distances than weakly sorbed compounds. Organochlorine pesticides are exceptions to these generalizations. Although strongly sorbing, these compounds have migrated substantial distances. The explanation for this anomalous behavior is not well established. Organochlorine pesticides were introduced to the groundwater system principally in solution with benzene, chloroform, or other organic solvents. Distribution coefficients for sorption presented in this report were obtained for single contaminants in solution with water. Distribution coefficients for sorption in a system of pesticides, organic solvents and water are likely to be substantially different.

Quantitative estimates of the distance of contaminant migration based on retardation factors given in Table 4.2 generally do not conform with observed migration distances. For example, the distance of migration by trichloroethylene predicted on the basis of the retardation factor in Table 4.2 is approximately 15 percent of the observed migration distance indicated in Appendix F, Figure 4.2-16. A retardation factor of 1.6 more closely matches the observed migration distance. A range of values between 1.0 and 1.8 was obtained for trichloroethylene during a two-well recirculating test in the Western Tier (Mackay, 1988, written communication).

4.6.5 Western Tier Pathways

Two major pathways for contaminant migration have been identified in the Western Tier. Water along these pathways occurs in alluvial sand and gravel. Saturated thickness varies from 10 to 70 ft. Hydraulic conductivity estimates obtained from long-term aquifer tests range from 400 ft/d to 1,500 ft/d. Hydraulic gradients typically are 0.005 ft/ft or less. Contaminants along both pathways flow toward the Irondale Containment System.

Assuming effective porosity values between 0.1 and 0.4, average linear velocity along the Rail Yard and Motor Pool Pathway ranges from 9.5 ft/d to 38 ft/d. Travel time from the

Motor Pool to the Irondale Containment System is between 0.7 years and 2.7 years. These estimates were obtained using hydraulic gradient extrapolated from Figure 2.4 and a value of 950 ft/d for hydraulic conductivity. Based on a retardation factor of 1.8 (Mackay, 1988, written communication), travel time for trichloroethylene is between 1.3 and 4.9 years.

Calculated values of average linear velocity compare favorably with the apparent velocity of DBCP (Figure 3.8). The distribution coefficient for DBCP is reasonably large, indicating that adsorption and retardation along the pathway is likely. Assuming that the distribution coefficient given previously for DBCP is correct, the rate of DBCP migration indicates that effective porosity is approximately 0.4 and the retardation factor is approximately 5.5.

Average linear velocity and groundwater travel time along the Western Tier Pathway has been calculated on the basis of hydraulic gradients indicated in Figure 2.4 and hydraulic conductivity equal to 950 ft/d. For values of effective porosity between 0.1 and 0.4, average linear velocity is between 9.5 ft/d and 38 ft/d. Travel time from the southern boundary of RMA to the Irondale Containment System is between 1.1 years and 4.3 years. The widespread distribution of contaminants along this pathway have precluded meaningful comparisons between calculated values and measured rates of migration. Average linear velocity along the Off-Post Western Tier Pathway and the Western Tier Pathway are similar.

4.7 Vertical Contaminant Migration

Contamination of the Denver aquifer primarily has been the result of downward migration of contaminants in groundwater from the overlying Unconfined Flow System. The most extensive contamination of the Denver aquifer is located in areas where sandstone or fractures provide direct hydraulic connection with contaminated groundwater in the Unconfined Flow System and hydraulic gradients indicate potential for downward migration. Rates of lateral flow in the Denver aquifer generally are not sufficiently high to interpret the distribution of contaminants on the basis of lateral migration.

In some cases, the depth of contamination is determined by the depth of interconnected sandstone zones in the Denver aquifer. Where sandstone zones are separated by claystone

or other material of low hydraulic conductivity, vertical migration into the lower sandstone is sporadic. Some wells that obtain water from the lower sandstone will be contaminated, while others show no evidence of contamination. In cases where sporadic contamination of a sandstone zone occurs, migration probably occurs through localized clusters of fractures.

Vertical contaminant migration has been most extensive in three areas of RMA. These areas are located near South Plants, Basins C and F, and the North Boundary containment System. Mechanisms and hydrogeologic conditions in each area are different. Therefore, the areas will be discussed separately.

In addition to these three areas, contaminants have been detected in isolated wells of the Denver aquifer in many parts of RMA. The distribution of these isolated detections was discussed in section 3.2.11. Because the detections are isolated, a detailed assessment of vertical contaminant migration is not possible. However, the most likely explanation for isolated points of contamination in the Denver aquifer is vertical migration through localized clusters of fractures. Migration along well bores is possible for those wells that were not constructed in a manner to prevent vertical intraborehole flow. However, this mechanism is not sufficient to explain most isolated detections.

4.7.1 South Plants

A limited number of contaminants have been detected in the Denver aquifer beneath South Plants and the distribution of contaminants is sporadic. The most frequently detected contaminant was chloroform. Other organic contaminants were detected infrequently. This is a sharp contrast to the larger number of contaminants detected in the Unconfined Flow System beneath South Plants. Sandstone zone A is the most extensively contaminated zone of the Denver aquifer. Other sandstone zones above and below zone A indicate sporadic contamination. The sporadic distribution of contaminants in the Denver aquifer indicates that the mechanism for vertical migration is very localized.

Sandstone zones beneath South Plants are separated from the Unconfined Flow System by volcanoclastic material with low matrix hydraulic conductivity. Rates of vertical flow through the matrix are not sufficiently large to explain the extent of vertical contamination. Matrix hydraulic conductivity estimated from cores as part of Task 26 is

less than 10^{-6} ft/d (Chen and Associates, 1987, written communication). Assuming a matrix hydraulic conductivity of 10^{-6} ft/d, an effective porosity of 0.10, and a unit vertical head gradient, the average linear velocity would be approximately 0.004 ft/yr. Actual average linear velocity through the matrix probably is less. On the basis of this velocity, vertical migration would not have extended more than 0.2 ft into the Denver aquifer from 1947 to present.

Contamination of the Denver aquifer beneath South Plants occurred by vertical migration through interconnected clusters of fractures. Cores obtained during well installation at South Plants frequently indicate the presence of fractures in the zone of volcanoclastic material. Fractures typically are subvertical with oxidized material coating the fracture surfaces. Below the first lignitic bed (approximately 50 ft below surface), fractures are less common. The evidence of fractures, in combination with the sporadic distribution of contamination in the Denver aquifer, indicates that migration along fractures probably has occurred.

4.7.2 Basins C and F

A large number of contaminants has been detected in the Denver aquifer beneath Basins C and F; however, contamination generally is restricted to sandstone zones 1 and 2. The list of contaminants detected in several wells includes chlorobenzene, chloroform, diisopropylmethyl phosphonate, oxathiane and dithiane. Most wells screened in sandstone zone 1 beneath Basins C and F indicate elevated levels of contaminants. However, the percentage of wells with detectable concentrations of contaminants decreases in sandstone zone 2.

Sandstone zone 1 beneath Basin C is in direct hydraulic connection with the overlying Unconfined Flow System. This provides a direct pathway for vertical migration. Present-day hydraulic gradients indicate a potential for downward flow. During periods when Basin C contained water, the water table in the Unconfined Flow System rose substantially and the potential for downward flow was enhanced.

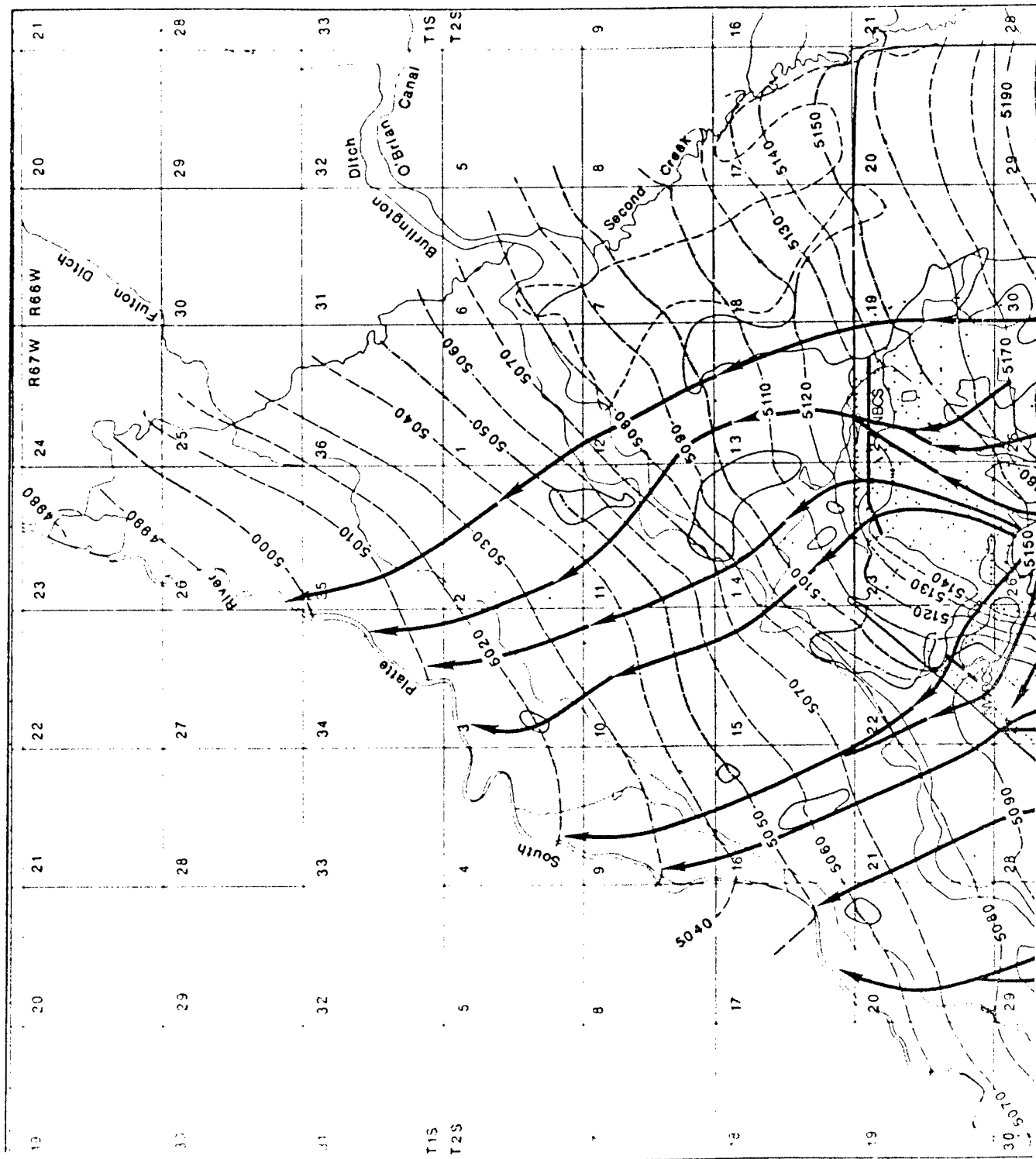
Sandstone zones 1 and 2 are separated by approximately 10 ft of claystone (Plate 2). However, the two zones probably are directly connected at some points below Basins C and F. Where connected, a pathway for vertical migration would occur. Hydraulic

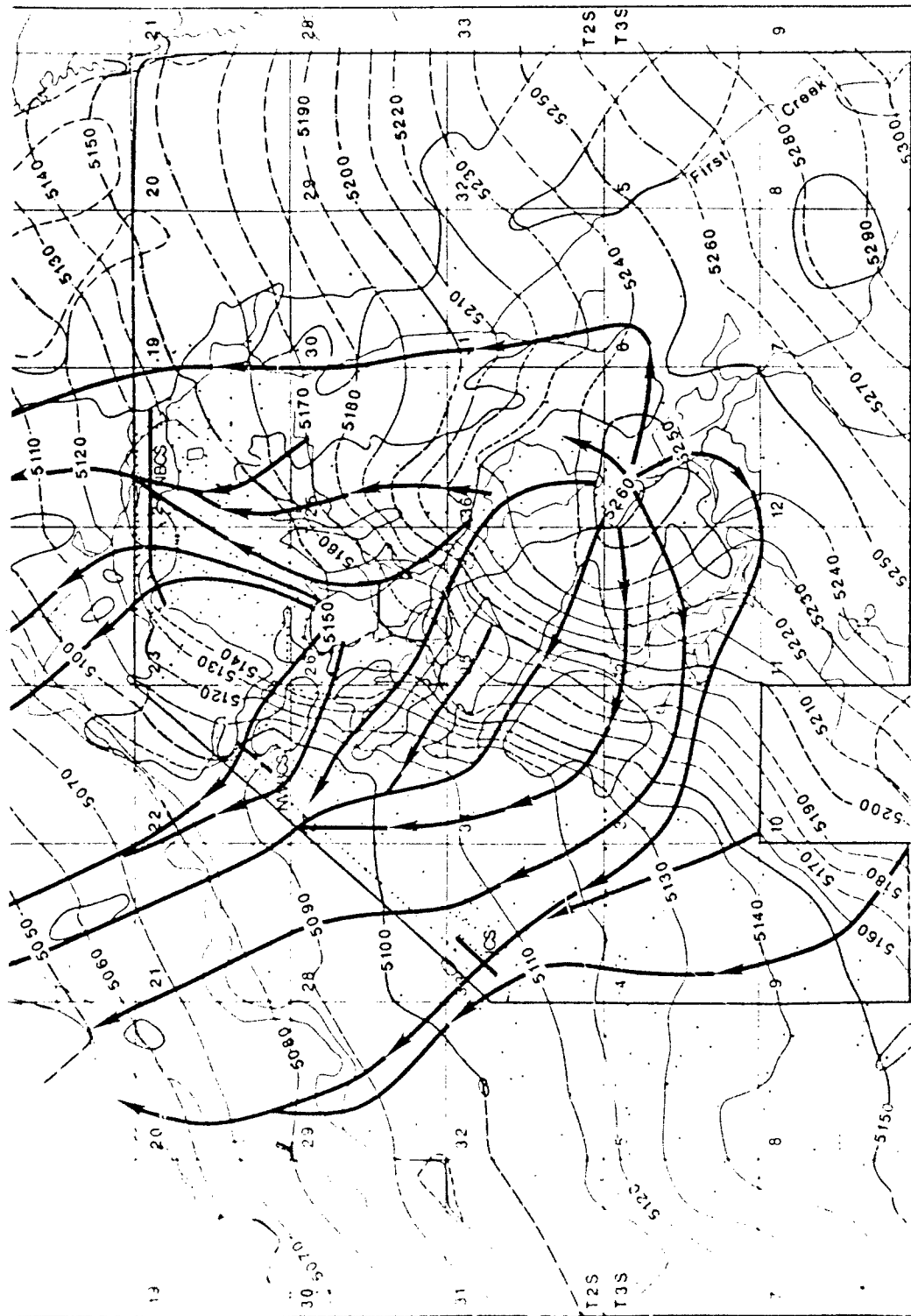
conductivity for zones 1 and 2 (Appendix F, Table 2.4-2), is between 10 and 30 ft/d. Assuming the two zones are directly connected, these values of hydraulic conductivity are sufficiently large to interpret vertical migration beneath Basins C and F on the basis of matrix flow through sandstone. A single well screened in zone 3 of the Denver aquifer generally indicates that most contaminants detected in zones 1 and 2 are not present in zone 3. This indicates that sandstone zone 3 probably is not directly connected to zone 2.

4.7.3 North Boundary Containment System

A large number of contaminants has been detected in the Denver aquifer beneath and immediately north of the North Boundary Containment System. Contaminants detected in several wells include benzene, chlorobenzene, chloroform, DBCP, dieldrin, diisopropylmethyl phosphonate, oxathiane, dithiane, trichloroethylene and others. Concentrations of some contaminants, including benzene and chlorobenzene, are higher in the Denver aquifer than in the overlying Unconfined Flow System. The elevated concentrations in the Denver aquifer indicate that vertical migration occurred in the past when concentrations in the Unconfined Flow System near the northern boundary of RMA probably were higher.

Contaminant concentrations above CRLs have been detected near the North Boundary Containment System in sandstone zones 2 through 5 of the Denver aquifer. These zones are interconnected or separated by thin intervals of claystone near the North Boundary Containment System. As a result, the mechanism for vertical migration between zones probably is by flow through the sandstone matrix. The sandstone zones are separated from the Unconfined Flow System by 10 ft to 20 ft of claystone. However, drilling near the North Boundary Containment System has indicated that part of the claystone is fractured. As a result, vertical migration of contaminants from the Unconfined Flow System to the shallow sandstone zones occurs through fractures.





EXPLANATION

Contour Interval Equals 10 Feet

Elevations in Feet

Datum Mean Sea Level

□ Unsaturated Alluvium

--- Inferred Contour

--- Interpreted Contour

→ Groundwater Flow Line

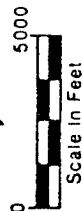
▲ Groundwater Monitoring Wells

ICS Irondale Containment System

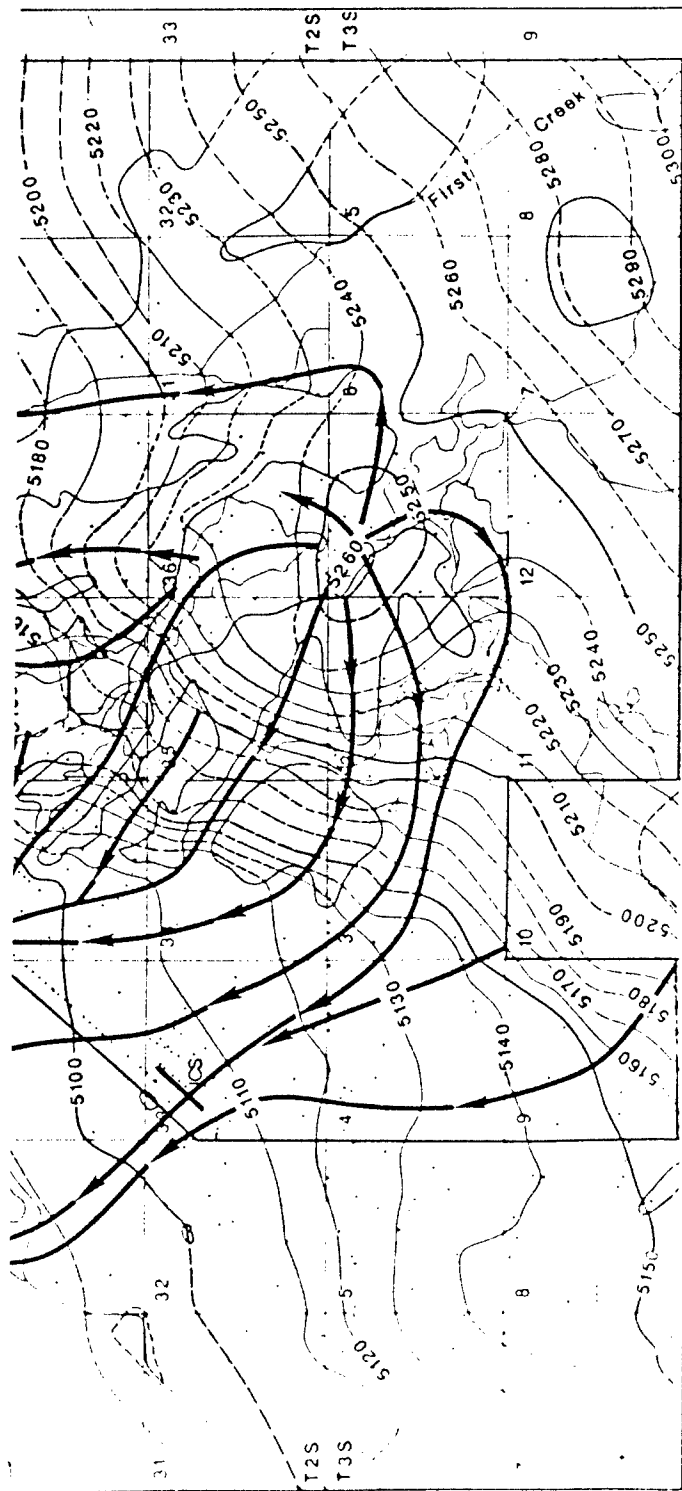
NBCS North Boundary Containment System

NWBCS Northwest Boundary Containment System

N



Scale in Feet



EXPLANATION

Contour Interval: Equals 10 Feet

Elevations in Feet

Cut-off Mean Sea Level

□ Unsaturated Alluvium

--- Inferred Contour

... Interpreted Contour

→ Groundwater Flow Line

▲ Groundwater Monitoring Wells

ICS Irondale Containment System

NBCS North Boundary Containment System

NWBCS Northwest Boundary Containment System

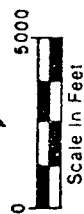
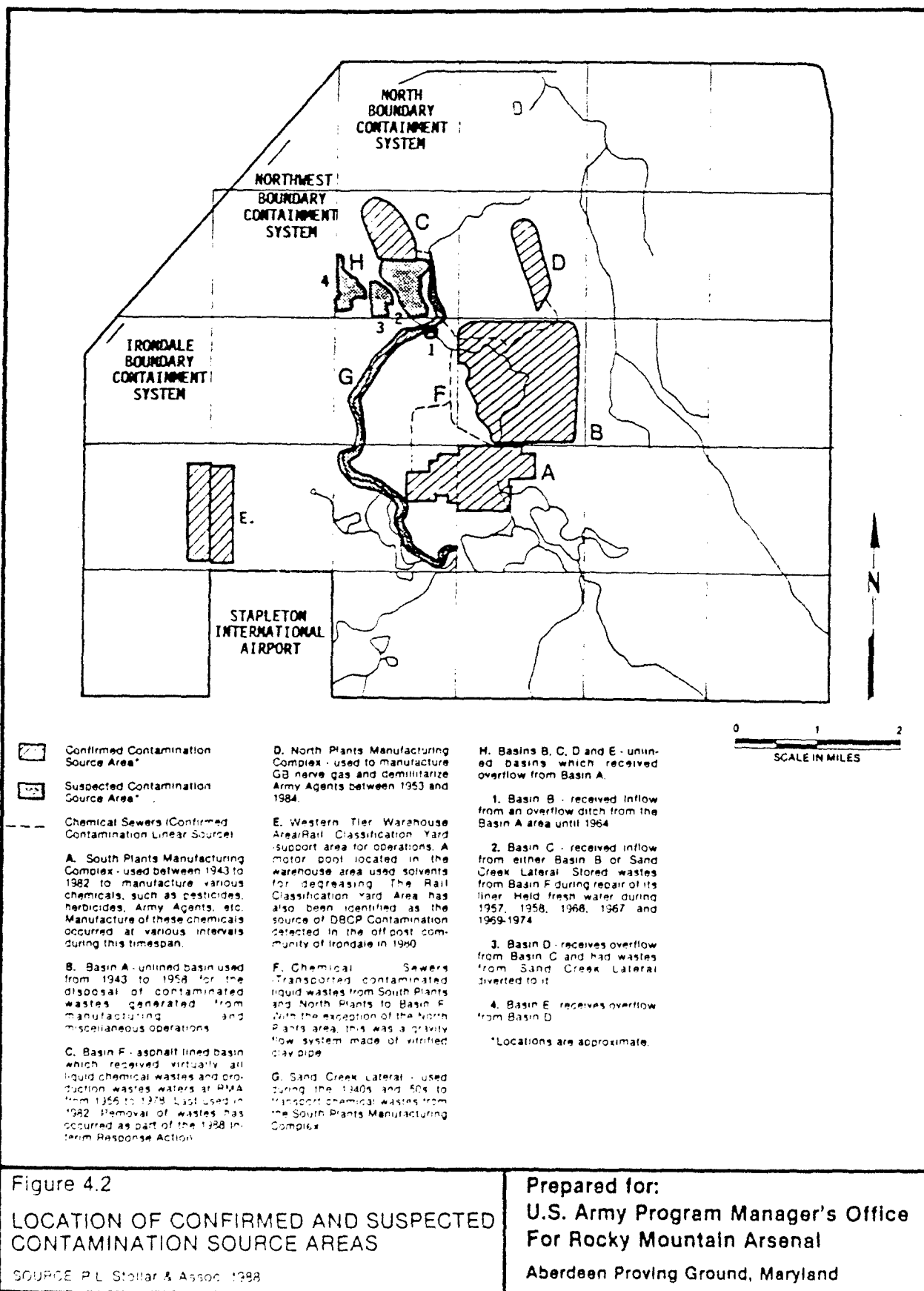


Figure 4.1

UNCONFINED FLOW SYSTEM CONCEPTUAL MODEL: WATER TABLE CONTOUR MAP AND GROUNDWATER FLOW DIRECTIONS

SOURCE: HCA, 1988

Prepared for:
U.S. Army Program Manager's Office
For Rocky Mountain Arsenal
Aberdeen Proving Ground, Maryland



5.0 SUMMARY AND CONCLUSIONS

The purpose of the Water Remedial Investigation Report is to assess contaminant occurrence and distribution within groundwater and surface water. To accomplish this, the RMA environmental setting was evaluated in terms of geology, hydrology, nature and extent of water-borne contamination, and contaminant migration.

Surface water at RMA flows within several small drainage basins that are tributaries of the South Platte River. The major drainages within RMA are First Creek and Irondale Gulch. Manmade structures including diversion ditches, lakes, and water retention basins have modified the natural drainage patterns. The land surface consists of gently rolling hills with a total change in altitude of 220 ft.

Groundwater at RMA occurs under both confined and unconfined conditions. The Unconfined Flow System includes saturated alluvium, eolian deposits and subcropping parts of the Denver Formation where lithologic data indicate the presence of sandstone or relatively permeable material. In areas where alluvial and eolian deposits are unsaturated, the Unconfined Flow System consists solely of sandstone and fractured rock within shallow parts of the Denver Formation. Saturated thickness varies from less than 10 ft to approximately 70 ft. Hydraulic conductivity estimates from aquifer tests range from 0.3 ft/d in areas where the Denver formation is unconfined to greater than 900 ft/d in alluvial terrace gravel.

Groundwater in the Unconfined Flow System generally flows toward the north and northwest. Spatial variations in hydraulic gradients and direction of flow is due to variations in saturated thickness, hydraulic conductivity, locations of recharge and discharge, and configuration of the bedrock surface. Water level fluctuations generally are small; however, seasonal fluctuations as large as 6 ft have been measured beneath South Plants. Historical water level fluctuations have been large in the vicinity of Basin C. During the late 1950s and from 1969 through 1975, water levels beneath Basin C rose 20-30 ft in response to artificial recharge. Present day recharge to the Unconfined Flow System occurs as infiltration of precipitation and irrigation, seepage from lakes, streams, reservoirs, canals, buried pipelines, and flow from the underlying Denver aquifer. Discharge occurs primarily as seepage to lakes and the South Platte River, groundwater withdrawals by wells, and flow into the Denver aquifer.

A numerical model of groundwater flow in the Unconfined Flow System has been developed to evaluate hydrologic concepts and refine hydraulic conductivity estimates. Model results confirmed that paleochannels and terrace deposits generally convey larger flow than interfluvial zones. Hydraulic conductivity estimates in the Basin A Neck and areas immediately northwest obtained during model calibration were smaller than initial estimates. Sensitivity analyses indicated that the areas of greatest model uncertainty within the boundaries of RMA are near South Plants and Basins A through F.

The Denver aquifer in the vicinity of RMA consists of parts of the Denver Formation where permeable sandstone or lignitic beds are separated from the Unconfined Flow System by relatively impermeable shale or claystone. The hydraulic conductivity of the shale and claystone matrix is small, probably 10^{-2} to 10^{-4} ft/d. The hydraulic conductivity for sandstone in the Denver aquifer has been estimated by aquifer test analyses to range from 1.1 to 7.7 ft/d. The hydraulic conductivity of fractured lignitic beds may be an order of magnitude greater than the hydraulic conductivity of sandstone.

Water in the Denver aquifer moves downward and laterally toward the northwest. The smaller hydraulic conductivity of shale relative to sandstone, as well as the stratification of the Denver aquifer, probably restricts the rate of vertical flow while enhancing lateral flow. Water in transmissive strata of the Denver aquifer returns to the Unconfined Flow System by lateral flow where the elevation of the bedrock varies appreciably in a short distance and the transmissive strata subcrop.

Areas where surface water contamination was detected include South Plants, Basin A and the Sewage Treatment Plant. Organochlorine pesticides and organosulfur compounds were the most frequently detected analytes. Fewer contaminants were detected from water entering RMA along the Peoria Interceptor. Comparisons of Third Quarter FY87 data with previously collected data indicate that there is little difference in analyte concentration at a site through time.

The majority of contamination by organic compounds occurs in the Unconfined Flow System. Plumes of organochlorine pesticides with peak concentrations greater than 1.0 ug/l have been identified in the South Plants, Basin A-Basin A Neck, Central, and Basin F pathways. Plumes of organosulfur compounds occur along the Basin A-Basin A

Neck and Basin F. Peak concentrations of 56,200 ug/l have been detected near Basin A for volatile aromatic organics. Plumes of volatile aromatic organics occur along South Plants, Basin A-Basin A Neck and Basin F pathways. Volatile halogenated organic plumes have been identified along all major pathways with peak concentrations of 39,800 mg/l occurring along the Basin F pathway. Numerous organic plumes have migrated along off post pathways.

Inorganic contaminants are more areally extensive in the Unconfined Flow System than organic compounds. Arsenic plumes have been delineated in the Basin A-Basin A Neck and Basin F pathways. The peak concentration of arsenic, 410 ug/l, occurred in the Basin F pathway. Fluoride concentrations greater than 5,000 ug/l were measured in the vicinity of Basin A and Basin F. Chloride concentrations greater than 1,000,000 ug/l were measured along the Basin A-Basin A Neck, Central, and Basin F pathways. The distribution of inorganic contaminants is complicated by the natural occurrence of these compounds.

Concentrations of organic compounds in the Denver aquifer generally are less than concentrations in the overlying Unconfined Flow System. Organochlorine pesticides generally occur in isolated areas, rather than plumes. Organosulfur compounds are common in upper stratigraphic zones of the Denver aquifer beneath the Basin A-Basin A Neck pathway and beneath Basin C. Volatile aromatic organics have been identified over a more extensive area than other organic groups. In many parts of RMA, samples from the deepest wells in the Denver aquifer contained measurable concentrations of one or more organic contaminants. Inorganic analytes above background levels are common in water of the Denver aquifer; however, concentration generally decrease with increasing depth.

Average linear velocity of groundwater calculated on the basis of available hydraulic information generally is consistent with observed rates of migration for weakly sorbing contaminants in the Unconfined Flow System. Dithiane and oxathiane are weakly sorbing contaminants that form plumes in the Basin A - Basin A Neck pathway. Average linear velocity of groundwater calculated from available hydraulic information compares favorably with actual contaminant migration rate assuming an effective porosity of 0.31. Other areas where average linear velocity compares favorably with observed migration rates of slightly sorbing contaminants include the Central and Basin F pathways.

The predominant hydrochemical processes affecting changes in contaminant concentration are sorption, vaporization, and degradation. Distribution coefficients (K_d) for RMA contaminants indicate that organochlorine pesticides generally are sorbed strongly while organosulfur compounds generally are sorbed weakly. Volatile aromatic organics and volatile halogenated organics tend to vaporize readily in the unsaturated zone.

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